Design of a Lithium Ion Battery Pack for 400 MPH Electric Landspeed Racing

THESIS

Presented in Partial Fulfillment
of the Requirements for Graduation with Distinction

By

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Abstract

For more than a decade the Buckeye Bullet landspeed racing team at The Ohio State University's Center for Automotive Research has pushed the absolute limits of electric vehicle racing. From batteries to hydrogen fuel cells, the team holds every national and international speed record in the unlimited class, with top speeds well into the 300 MPH range. The mission statement of the team is to push the technologies of tomorrow to their absolute performance limits. With this mission in mind the team is currently developing the ultimate landspeed electric vehicle, the Buckeye Bullet 3, which will be powered by the latest generation of lithium ion batteries. For the first time since 1899, an electric vehicle will be designed with the intent of directly competing with its fossil fueled counterparts. The team hopes to push the electric landspeed record over 400 MPH and eventually set the ultimate wheel driven record in excess of 450 MPH. This document investigates the design of the lithium ion battery pack with respect to battery cell testing and selection, electrical power performance, system safety design, thermal management, component testing and integration, mechanical packaging, and modeling and simulation. This project reports on and builds upon work on the development of this system from 2009 to 2012. The document concludes with a description of future work needed to complete the battery pack integration and prepare the energy storage systems of the vehicle to break a 400 MPH+ world record.

Dedication

This document is dedicated to my parents for their extraordinary dedication to, involvement in, and support of all aspects of my life. I am eternally grateful for their extreme sacrifices in the name of their children's success. They have always been and will always be my greatest inspiration in life.

Acknowledgments

I would like to thank a number of people who have made this program and my personal mission a reality. First of all, Buckeye Bullet graduate students LingChang Wang and Josh Terrell, for their direct assistance in this project. Ling, Josh, and I have worked together as a team on the development of the battery system and a great deal of the work presented in this document is a collaborative effort. It has been a pleasure to work with such talented and dedicated student engineers. I would also like to thank all of the Buckeye Bullet team members, sponsors, and advisors for their continued support and dedications. I would especially like to recognize the efforts of our faculty advisor Dr. Giorgio Rizzoni in his assistance in the development of the program and specifically for his support of my academic and professional career. I would also like to recognize our drive Roger Schroer and thank him for his extreme dedication to the students and for being an excellent mentor and roll model. In addition the entire faculty and staff of the Center for Automotive research have been instrumental in our success as a team. The efforts of John Neal and Dr. Yann Guezennc in providing access to the battery labs, and testing assistance have been extraordinary. Finally I would like to thank Venturi Automobiles and their president Gildo Pastor for his amazing level of support for our racing program, as well as my academic career. His support has allowed us to transform our dreams into reality.

Vita

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Program History

For the past 20 years, students at The Ohio State Universities' Center for Automotive Research have been designing, building, and racing electric vehicles. The program started with a open wheel formula style car named the Smokin' Buckeye which raced in the Formula Lightning series which is shown in Figure 1 below.

Figure 1: OSU Smokin' Buckeye - Formula Lightning Series Race Vehicle

The team was incredibly successful in winning more than half of the races in the series and every national championship that was awarded. In 2001 the Formula Lightning series ended and the team decided to attempt a new challenge; setting a world speed record for electric vehicles. This was the beginning of the Buckeye Bullet landspeed racing program. Over the past ten years, the team has developed three different electric landspeed streamliners with power sources ranging from nickel-metal hydride and lithium ion batteries to hydrogen fuel cells. The team currently holds all of the national and international records in the unlimited weight class for electric vehicles for both battery and fuel cell power sources. Each of these records is in excess of 300 miles per hour and still stand as of 2012. These records setting vehicles are shown below in Figure 2, Figure 3, and Figure 4.

Figure 2: Buckeye Bullet 1 - 314 MPH - NiMH Batteries - 2001 to 2004

Figure 3: Buckeye Bullet 2 - 303 MPH - Hydrogen Fuel Cell - 2006 to 2009

Figure 4: Buckeye Bullet 2.5 - 308 MPH Li-Ion Batteries - 2010

The team has established two main missions. The first to provide a truly unique opportunity for students to apply their engineering knowledge outside the classroom, and to develop the next generation of leading edge automotive engineers. The second mission is to take the powertrain technology of tomorrow and test it to its' ultimate limits today, showing the world that green technologies of the future can still be rooted in performance. The ecologically friendly innovations of the auto industry do not have to bring an end to racing, merely a revolution.

1.2 Landspeed Racing

Landspeed racing quite different from any other form of racing. Many herald it as "The last pure form of grassroots motorsports." Each year thousands of gear-heads travel to the Mecca of landspeed racing, The Bonneville Salt Flats, in Utah. The flats is a 50 square mile, dry lake bed. Each winter year the entire area floods, becoming a salt lake, but in the late spring and summer the water recedes leaving a perfectly flat salt surface. The salt flats are so large they can be seen from space as shown in Figure 5.

Figure 5: Bonneville Salt Flats, Utah

Automobile racing at Bonneville dates back to the turn of the 20th century. As long as there have been automobiles man has been driving them to the limits, frequently choosing the Bonneville as the location for top speed trials. In the 1950's an official yearly hot rod speed trail event was created. Each year more than 500 teams bring cars spanning hundreds of categories to compete at Speedweek, the largest of 5 major events that take place on the flats. There is quite literally a class for any type of powered vehicles, including numbers Frankenstein like creations that didn't even begin as automobiles. From showroom stock OEM cars to fighter jet fuel tanks with a seat and motor bolted inside, if it can move under its' own power it has probably raced at Bonneville.. Aside from the location, the track, and the cars, the most unique part of the landspeed racing community is the relationship between the competitors. Most other forms of racing have a very closed feel, with development happening behind locked doors and limited access pits at the track. The rules of the racing body are very specific and hinder engineering creativity. Slight advantages from minor changes in tuning is all that separate first and last place so the winning configurations are highly guarded. The Bonneville experience is quite the opposite. Though there is a rule book, nearly all of the rules are dictated by safety and great work is taken to make sure that creativity is not limited, but instead encouraged. The majority of the rules are simply to classify the vehicles into the various categories. At the track the pits are completely open and the competitors are more than willing to discuss their designs, experiences, and trade secrets. It is not uncommon to see the current record holder coaching a competitor and suggesting design improvements, or even taking parts from their own vehicle to help repair a competitors vehicle so they can have a shot at a new record.

There are many different sanctioning bodies which grant landspeed records. In the United States, sanctioning body which grants national records is the Southern California Timing Association. Internationally sanctioned records are granted by the FIA (Federation Internationale de l'Automobile). Records are always based on the average of two runs, a qualifying run in which the previous record must be surpassed by at least 0.001 mile per hour, and a record run which occurs after a successful qualifying run. The specific rules of vehicle classification, track layout, and record certification vary greatly among sanctioning bodies. The course layout for national and international records are shown in Figure 6 below.

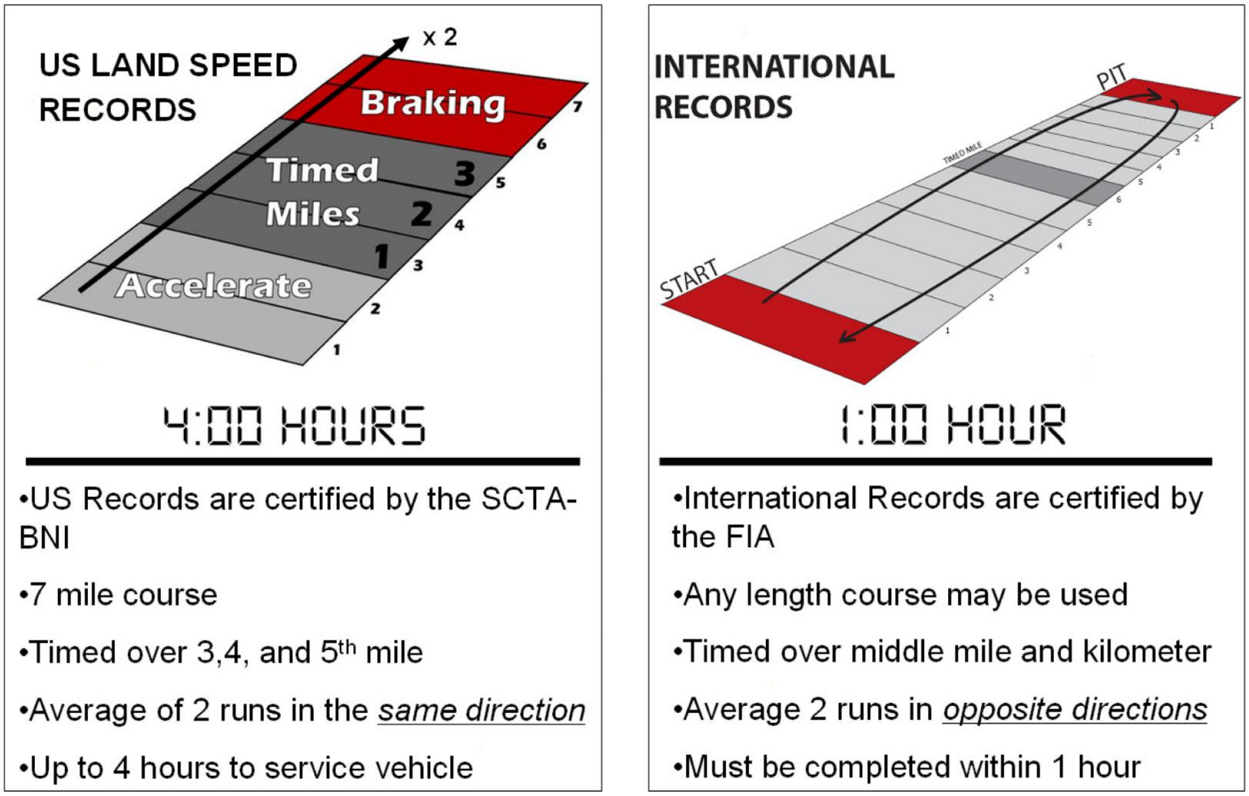

Figure 6: Landspeed Racing Course Layout

For the national record two untimed miles of acceleration are followed by three time miles. The average speed over each mile is calculated and the fastest mile is considered the attempt speed. At least two miles of stopping distance follow the timed miles. If the run qualifies for a record, the vehicle must report to impound and the team has four hours to service the vehicle. The vehicle is kept in impound overnight and a record run takes place first thing the next morning, in the same direction on the same track. During the record run the average speeds over miles 3,4, and 5 are again recorded. It is important to note that the speeds averaged for a record must occur in the same physical mile for both the qualifying and record runs.

The course layout and rules for an international record vary greatly. In the case of the international record the acceleration period and overall track length are not specified. The only requirement is that a "flying mile" be marked somewhere on the course. This is the only timed section of the course. Like the national records, the speed is calculated as the average speed over the timed mile. The rules are such that a record attempt course could be set up anywhere in the world. In the case of Bonneville the longest high quality stretch of salt is approximately 11 miles. The flying mile is set up in the middle with approximately 5 miles of acceleration approach on either side. The two runs must be completed in opposite directions within one hour of each other. This is to account for changes in grade and wind speed. While there is nearly no grade at Bonneville, this rule is necessary to ensure fair conditions at other tracks around the world. The one hour turnaround time becomes a huge factor in racing strategy for the teams. The clock starts as soon as the vehicle enters the timed mile and the vehicle must exit the timed mile on the return run within the allotted 60 minutes. This means that after considering the stopping period in the first run and setup and acceleration periods during the second run, approximately 30 minutes are left for vehicle service in the pits. In the case of a battery vehicle this leads to the major decision of whether to charge or swap batteries. If a charging strategy is chosen, the amount of charge that can be put into the batteries becomes a major design parameter and has a large effect on the maximum speed of the return run.

1.3 Motivation: Buckeye Bullet 3

In 2009 the team concluded the Buckeye Bullet 2 (BB2) hydrogen fuel cell program and actively began the search for a new challenge. Staying within the program mission of utilizing alternative technology to break world speed records the team became very interested in many of the new battery technologies on the market. The team had not been engaged in battery research since the conclusion of the Buckeye Bullet 1 (BB1) program in 2004. During the 5 years of the hydrogen program, battery technology changed drastically. It became evident very quickly that a with the increased power and energy density of modern batteries, a much more efficient and thus faster battery vehicle could be developed. In late 2009 the team began the concept phase of defining a new battery vehicle program, The Buckeye Bullet 3 (BB3). With the electric vehicle records in hand, it was time to raise the level of expectation of the program and begin to compare electric vehicles to their gasoline counterparts. In landspeed racing the first digit of a speed record is the only one that really matters. A 299 MPH record still places you in the 200 MPH club, but increase that by one MPH and suddenly you are in the 300 MPH club. The Bullet program had performed at the 300 MPH level repeatedly and successfully, so 400 MPH was decided to be the next obvious challenge. Further investigation into the top speeds of internal engine powered traction vehicles showed that the fastest piston engine vehicle is currently the Burkland Streamliner at 415 MPH, as seen in Figure 7. The ultimate wheel-driven record is held by a turbo shaft powered vehicle, the Vecso Turbinator at 458 MPH, as seen in Figure 8..

Figure 7: Burkland 411 Streamliner - Current Fastest Piston Engine Vehicle 415 MPH

Figure 8: Vesco Turbinator - Current Wheel Driven Record - 458 MPH

Very few wheel-driven vehicles have ever broken 400 MPH. A listing of all of the vehicles that have achieved this feat are listed in Table 1 below. There have only been 9 vehicles to exceed 400 MPH and not even all of those established an actual 2 direction certified record.

Table 1: Wheel-Driven Runs Over 400 MPH

Vehicle	Team	Year	Speed	Powered By
Bluebird CN7	Donald Campbell	1964	403.100	1 Engine, TurboShaft, 4WD
Goldenrod	Summers Brothers	1965	409.277	4 Engine, Unblown, 4WD
Speed-O-Motive	Al Teague	1991	409.86	1 Engine, Blown, Fuel, 2WD
Turbinator	Team Vesco	2001	458.440	1 Engine, TurboShaft, Fuel, 4WD
Spirit of Auto Power	Nolan & Rick White	2002	413.000	2 Engine, Blown, Fuel
Burkland s 411	Burkland Family	2008	415.896	2 Engine, Blown, Fuel, 4WD
Spirit of Rett	Charles Nearburg	2010	414.316	1 Engine, Unblown, Fuel, 2WD
Speed Demon	Poteet and Main	2010	404.562	1 Engine, Blown, Fuel, 2WD
Spectre SpeedLiner	Spectre	2010	408.000	1 Engine, Blown, Gas, 2WD

With these records in mind the team set out with a renewed passion to develop the Buckeye Bullet 3. It was evident that to create a vehicle to exceed 400 MPH and eventually contest the ultimate wheel driven record, every system would have to be designed from the ground up as a purpose built and fully optimized solution. Nearly every area of automotive and aerospace engineering would need to be implemented including optimization in aerodynamics, energy storage, powertrain design, lightweight structures, materials joining, control systems, and power electronics. Early concepts of the aerodynamic and packaging studies are shown in Figure 9 and Figure 10. To get maximum powered to the ground both axles needed to be powered making the BB3 the team's first all-wheel drive vehicle. The driver was also moved in front of the front axle for optimal aerodynamic performance and packaging efficiency.

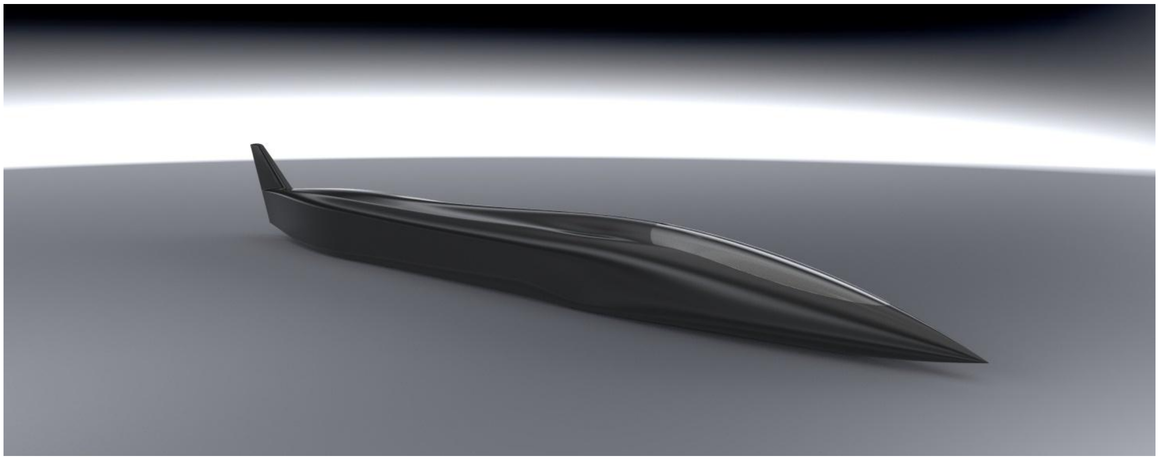

Figure 9: Buckeye Bullet 3 Concept

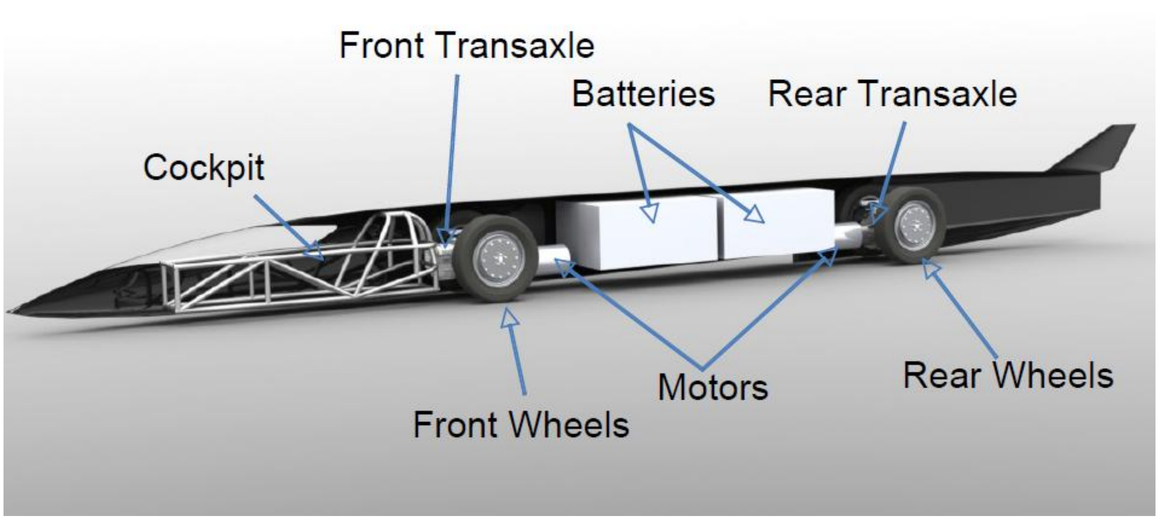

Figure 10: BB3 Proposed Layout

The only components carried over directly from previous vehicles were the driver and the tires. While every other system was completely new for BB3, the previous knowledge gained from 10 years of electric landspeed racing experience was called upon frequently in defining each system. An intensive simulation exercise was preformed to better understand the performance capabilities of a modern electric traction drive system. A full sweep of many vehicle configurations and power levels were considered. Simulation results show a properly designed, implemented, and optimized electric traction vehicle could actually exceed 500 MPH on the current FIA course at Bonneville, as seen in Figure 11.

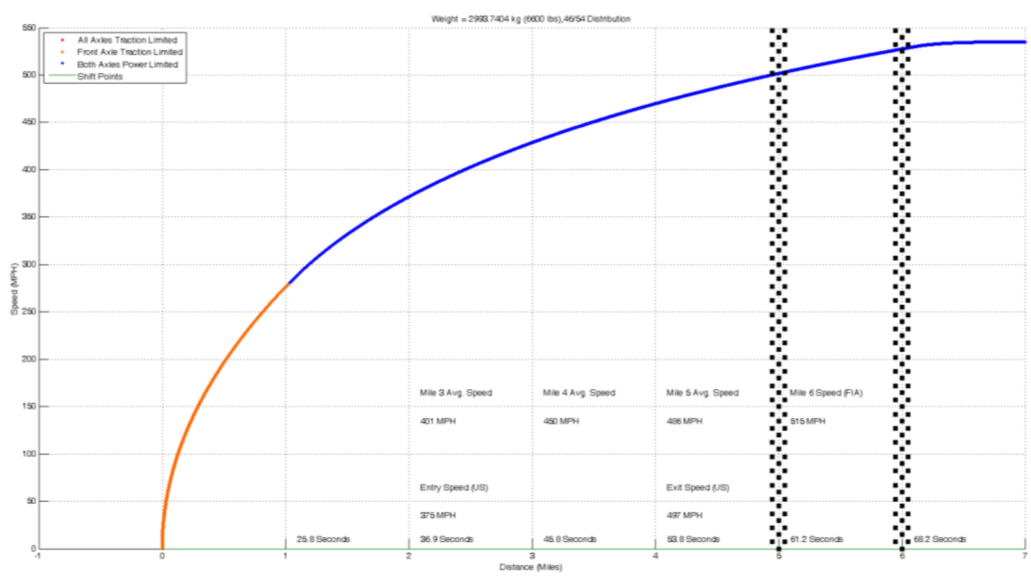

Figure 11: BB3 Performance Potential

While most of this simulation is rooted in well proven models and historically accurate methods, the one major idealized assumption to this exercise is that a perfect traction control system can be implemented and that the surface consistently exhibits a coefficient of friction of 0.6. In reality the coefficient along the salt varies greatly in both time and location. A range of more than 0.3 can be seen at different points along the track on a single run. In addition, implementing and tuning a perfect traction control system is large undertaking, and will definitely not be completed in the initial testing phases of the project.

While all of the systems require a high level of engineering optimization, the two most critical systems are the electric powertrain, and the on board energy storage, or battery system. The powertrain specifications have been established by the team, and the system is currently being developed in conjunction with Venturi Automobiles, a European electric vehicle specialization company. A detailed look into the development of the battery system is the subject of this document.

A critical part of landspeed vehicle development is first understanding what power is required to overcome the vehicle losses, aerodynamic drag, mass accelerations, rolling resistance, etc; and then to gain an understanding of which areas have the potential to be improved. While it is very true that at high speed from a magnitude perspective aerodynamic losses dominate, the window of possible improvement is very narrow. The difference between a well designed aerodynamic strategy and an extremely optimized system is very narrow. On the other hand the mass and volume of the battery system is an area that can be highly optimized an lead to significant overall performance gains. An early high level estimation of energy storage needs showed the battery system could vary more than 2000 pounds based on the use of various technologies, packaging strategies, and integration methods. This variance led to a total vehicle mass of 6000 to 8500 pounds. As seen in Figure 12, this range of mass leads to more a performance window gain of more than 50 MPH at the end of the run.

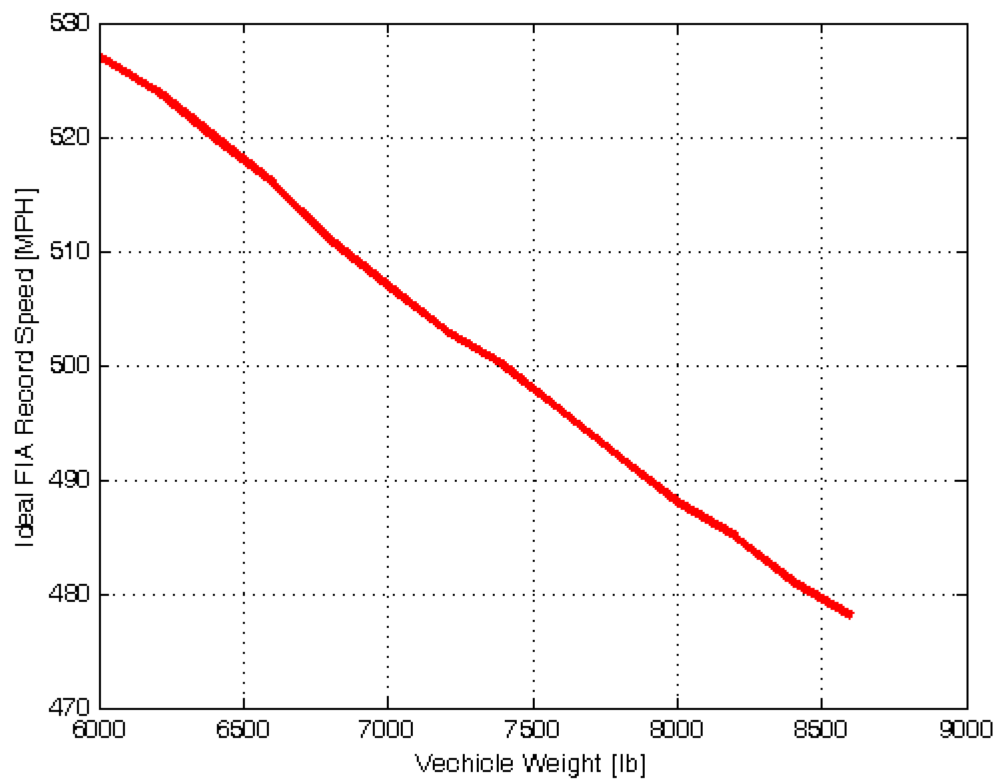

Figure 12: Effect Of Vehicle Weight On Speed

In a world where every 0.1 MPH is difficult to gain, and the difference between setting records and going home empty handed is quite small, 50 MPH from one system optimization is noting shy of amazing. From a mass prospective along, this sensitivity study sets the tone for the importance of complete battery system optimization. When coupled with the relationship to the power capabilities of the driveline, and the overall vehicle safety which is the number one concern of the team, it becomes clear that the proper development of a battery system is one of the most important objectives of the entire Buckeye Bullet 3 program.

1.4 Thesis Objectives

The objectives of this document are to:

- Introduce Battery Technology and Concepts Relevant to Battery Pack Design
- Document and Detail All Battery Pack Development Work From 2009-2012
- Present Battery Testing Procedures and Results
- Present Component Selection and Design
- Review Safety Considerations and Safety System Implementation
- Present Complete System Design Proposal
- Introduce Battery Modeling Concepts
- Document Future Planned Development

1.5 Thesis Summary

This document is divided into 7 chapters. The first chapter provides an introduction to Buckeye Bullet program and sets the context for the battery pack development project. The second chapter introduces battery technology and system architecture and presents the historical prospective of Buckeye Bullet battery packs. The third chapter describes battery testing procedures and presents an overview of test results. The fourth chapter explores safety consideration as well as the process of defining additional system components needed and the methods for the design and selection of these components. The fifth chapter details the mechanical packaging layout, design, and component integration. The sixth chapter introduces battery modeling concepts and describes the work completed thus far. The seventh and final chapter describes plans for future work.

Chapter 2: Literature Review

2.1 Introduction To Batteries

From cell phones and laptops, pacemakers, to cars, batteries are a part of the daily life of nearly individual living and working in a developed county. In scientific terms, a battery is an electro-chemical energy storage device. This means that through a chemical reaction a battery has the ability to sore and later deliver electrical energy. There numerous types of batteries in all shapes and sizes. The basic configuration of a battery is shown in Figure 13 below.

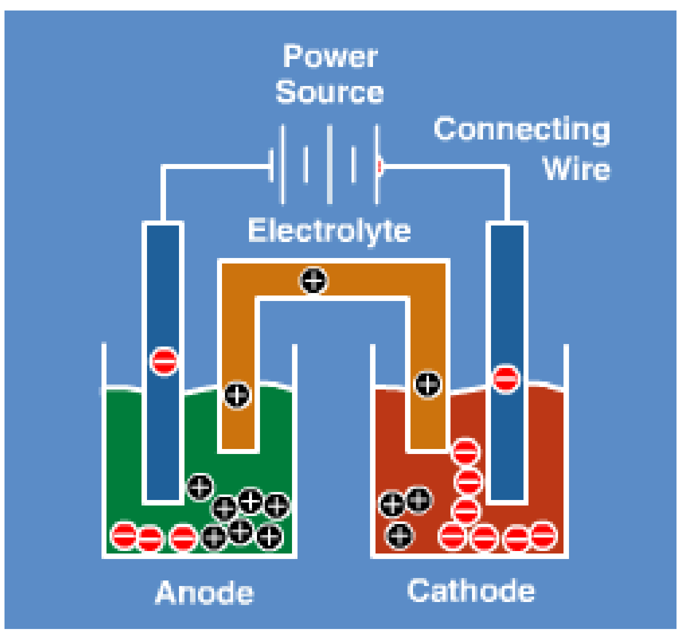

Figure 13: How A Battery Works (Courtesy of www.altenergymag.com)

The cell is made up of an anode or negative terminal and a cathode or positive terminal. The battery is also filled with an electrolyte, usually a liquid. The chemical interactions between the materials that make up the anode and cathode and the electrolyte created a difference in electrical potential, or voltage between the positive and negative poles. Connecting these poles to an electrical circuit allows electrical energy to be removed from the battery as the chemical reaction occurs, until the reaction is complete and the battery is "empty." Depending on the specific chemistry the reaction may or may not be reversible, or in other terms the battery may or may not be rechargeable.

The most common way to classify batteries is by their chemistry, or the materials and reactions taking place in the cell. A few of the more common chemistries are:

- Alkaline
- Lead Acid
- Nickel Cadmium (NiCd)
- Nickel Metal Hydride (NiMH)
- Lithium Ion (Li-Ion)
- Zinc-Carbon
- Molten Salt (Sodium-Sulfur)

For the remainder of this document only Li-Ion batteries will be considered. The Buckeye Bullet team and the researchers at the OSU Center for Automotive research have many years of experience in working with batteries of all types. Under the scope of this document it is assumed that all battery types have been considered and Lithium-Ion chemistries are most appropriate for the application. From this point forward the difference between different types and suppliers within the Li-Ion family will be considered.

2.2 The Battery Cell

From the consumer prospective the only battery parameter that really matters is capacity. From cell phones to electric vehicles, all people want to know is how long it will last before a recharge, making the selection of a battery fairly straightforward, the bigger the better. From an engineering design prospective though a battery is a relatively complex device. The smallest unit of a battery system is the cell. One cell usually represents the smallest useable unit of anode and cathode producing the voltage established by the chemistry. In some cases, such as automotive lead acid batteries several cells are combined in one inseparable package to meet certain system parameter, but this is actually a small system, not a single cell.

A great deal of battery performance can be studied on the cell level. For the most, with the exception of thermal considerations, battery performance scales quite well from the cell level. If complete characterization of cell parameters is performed, simulations of complete systems is very straight forward. With this in mind it is important to understand the parameters that effect battery performance. Electrical power is the combination of the current flow and the operating voltage of the system. While the minimum and maximum bounds of the voltage of a battery are defined by the chemistry, the actual operation voltage is a reasonably complex parameter. Voltage is heavily affected by operation temperature, state of charge, and discharge rate. Figure 14 below shows typical discharge curves for a lithium-ion battery. The plot displays the cell voltage over the state of charge (SOC) of the battery with 100% SOC on the left transitioning to 0% SOC on the right. By following one discharge curve, it can be seen that for this chemistry the cell begins at a high open circuit voltage at full charge, but quickly decreases after 1% discharge. The voltage is reasonably flat for majority of the operating range of the cell, but decreases sharply at about 20% SOC.

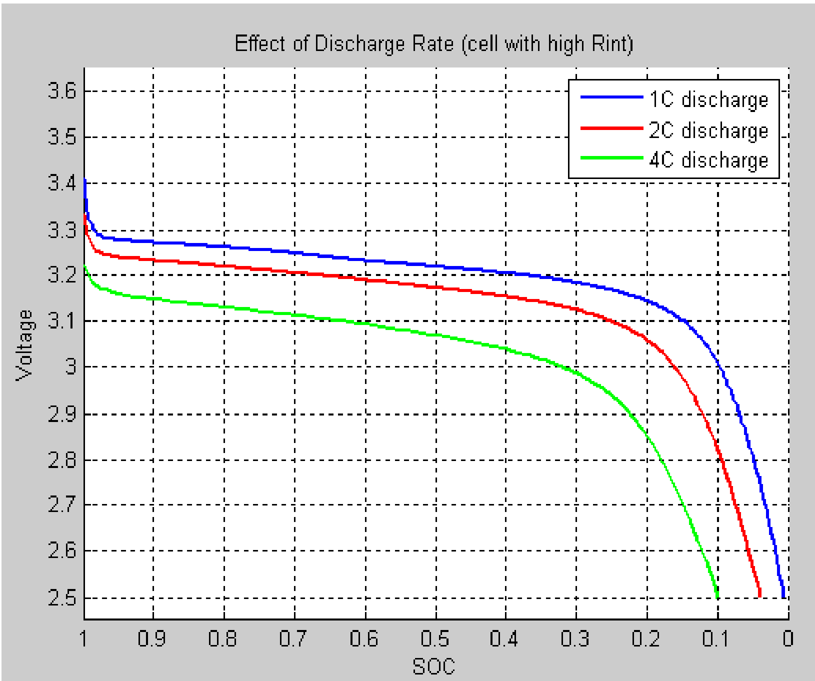

Figure 14: Effect of Discharge Rate On Voltage

A common metric for discharge rates of batteries is the C rate. This metric does not only consider the actual magnitude of the current flow, but instead relates the current flow to the overall battery capacity. The C rate is directly proportional to the discharge current and inversely proportional to the length of time it takes to fully discharge the battery. A C rate of 1 corresponds to a one hour full discharge. A C rate of 30 corresponds to a 2 minute full discharge, but at a much higher discharge current than a C rate of 1 for the same battery. In addition to demonstrating the general shape of the voltage discharge curve, Figure 14 above also displays discharge curves for several different C rates. It can be seen that discharging a cell at a higher rate results in an overall downward shift of the voltage concern. While this phenomenon might not have significant impact on the single battery present in a TV remote control, when the battery system is instead powering an electrical motor and the 300 mV difference is multiplied across many batteries in series, there is a significant overall voltage drop which can lead to a significant impact on overall system performance.

The next major factor affecting cell performance is temperature. The voltage of a cell is highly dependent on the operating temperature. In general, within the acceptable operating bounds, the higher the temperature the higher the voltage. Figure 15 shows two discharge curves for the same cell and discharge rate, but with an 8 degree difference in the cell temperature at the start of the test. Even at this small temperature differential, the effect on voltage is clear. As stated above, even small deviations in the voltage at the cell level compound to significant pack level voltage for the entire system. Operating temperature needs to be carefully considered in all battery system designs, but is especially important when the power electronic that the batteries supply have hard voltage limits (minimum and maximum), as is the case in the Buckeye Bullet powertrain.

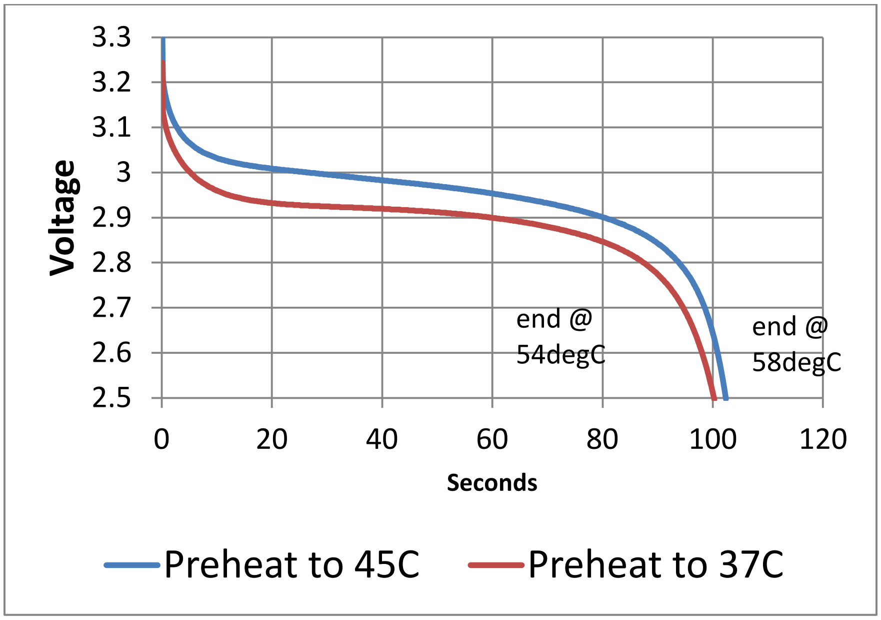

Figure 15: Effect of Operating Temperature On Voltage

2.3 Battery Systems - Forming A Pack

With an understanding of basic cell performance parameters, the next important topic is how cells are combined together to form battery packs. Electrically cells can be connected together in series and parallel to achieve the necessary overall system voltage and capacity. Figure 16 shows how batteries are connected in series and parallel schemes and the resulting system parameters. This visual is based on a typical 1.5 volt two amp hour capacity. The capacity for a battery is rated as the amount of current the battery could discharge continuously to deplete all of its energy in a one hour period, thus the amp-hour rating.

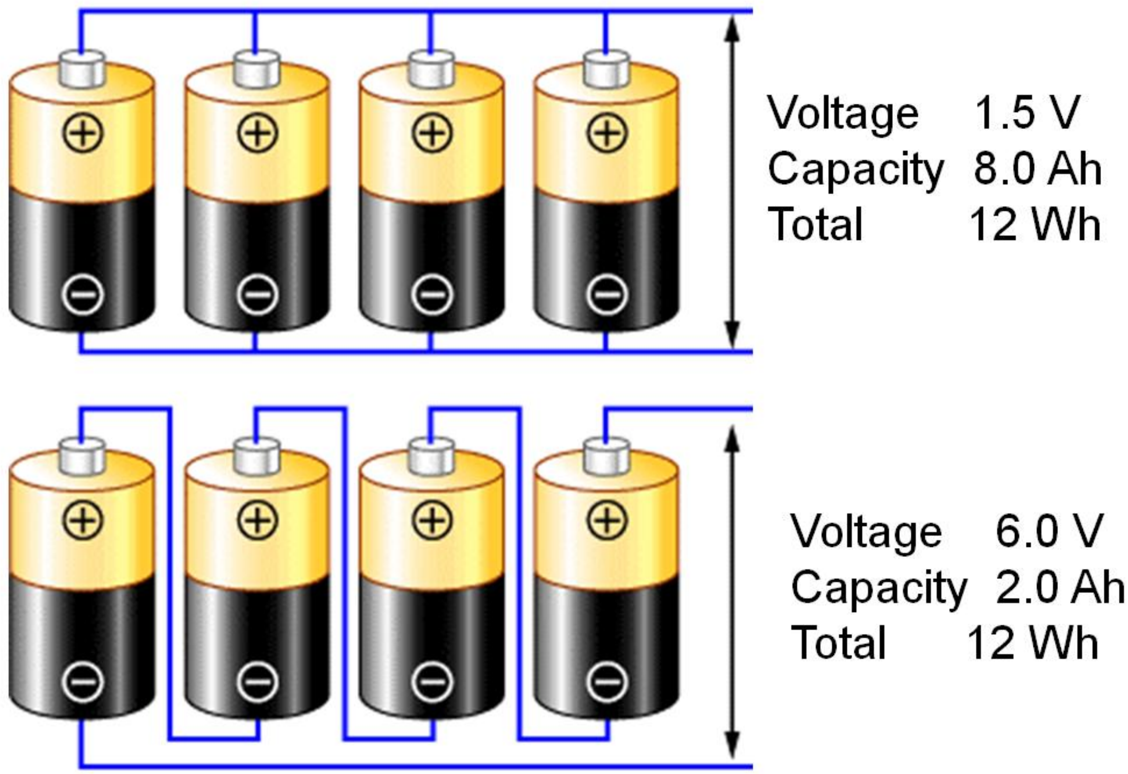

Figure 16: Parallel (Top) and Series (Bottom) Configurations

To connect batteries in parallel all of the cathodes are connected together as one terminal and all of the anodes are connected together as the opposite terminal. This layout provides a voltage equal to that of one cell, but a capacity equal to the cell capacity times the number of parallel elements. The system at the top of Figure 16 would be reported as a 1S-4P system. In contrast a series connection is formed when the anode of one battery is connected to the cathode of the next battery in a continuing chain. The voltage of the system is equal to the voltage of a cell times the number of series elements, but the capacity is only that of one cell. The system at the bottom of Figure 16 would be reported as a 4S-1P system. is important to note that the power-capacity rating is conserved in both cases. With this example it can be seen that series elements are added to achieve the required voltage and parallel elements are added to achieve the required capacity, or in other terms, divide the current draw among multiple cell strings. To calculate the needed number of series and parallel elements Equation 1 and Equation 2 below can be used.

Equation 1: Number of Series Cells

$$\#Series = \frac{V_{dc\_bus\_\max}}{V_{cell\_\max}}$$

Equation 2: Number of Parallel Cells

$$\#Parallel = \frac{I_{\max}}{I_{cell\_\max}} = \frac{I_{\max}}{Capacity \cdot C_{rate\_\max}}$$

After determining the number of series and parallel elements needed, the electrical structure must be determined. In the simplest terms the designer must decide if cells will be connected in series first and then the series string in parallel, or the opposite. The two basic options are displayed in Figure 17.

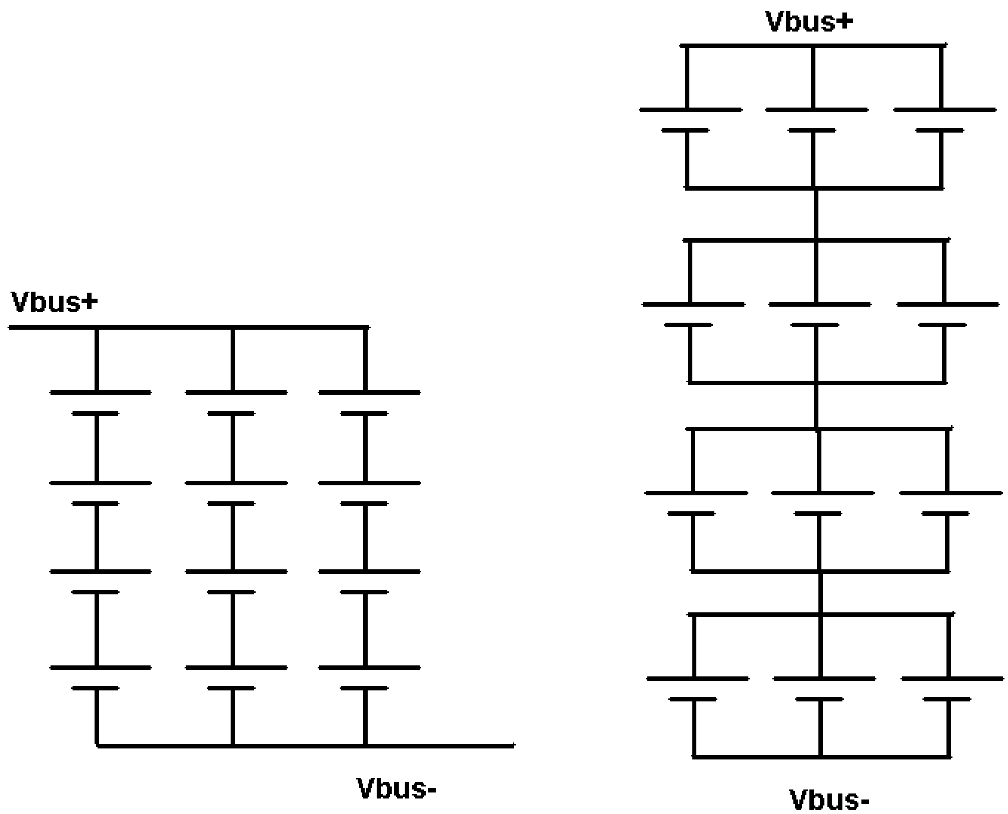

Figure 17: (Left) Parallel Groups Of Series Cells, (Right) Series Groups Of Parallel Cells

The decision of which strategy to use is one of continual debate and requires consideration of many system parameters and design constraints. In general is it reasonable to state that the preferred method is to have parallel connections at the cell level. This strategy has a few benefits. First of all this keeps parallel string forced to the same voltage and thus prevents the possibility of circulating currents from an imbalance in charge between parallel elements. Circulating currents between strings can cause a great deal of harm and even complete failure of a battery system. If the alternative strategy is used with series strings in parallel diodes must be used on each string to prevent circulating currents, which leads to a great deal of additional system complexity and added components. The parallel first strategy also keeps sub modules at lower voltages that are safer to handle since there are less series elements in within each module. Finally the parallel first strategy requires less control electronics. In a lithium pack, as will be discussed in Chapter 4, it is critical to monitor voltage at ever series connection to ensure proper operation. If the cells are in parallel the total number of voltage measurements is equal to the number of series elements, but if the cells are in series first the number of measurements is the number of series cells times the number of parallel cells. Every cell in the pack must be monitored. This adds cost and complexity to the control system. On the other hand, when cells are put in parallel first, all of the system components see the full pack current meaning that all of the wiring, connectors, and system components must be able to handing the full discharge current. In large systems this could mean a significant increase in the size of all of the sub pack components.

The general terminology for battery unit hierarchy used in this document are as follows:

- <u>Cell</u> - The Simplest and Smallest Battery Unit, No Control Or Monitoring
- <u>Module</u> - A Collection of Cells Contained Within Factory Packaging and Including A Voltage and Temperature Measurement Board
- <u>Battery Pack</u> - A Complete System Containing Multiple Modules, an Overall Supervisory Management System, and a Thermal Management System
- <u>Vehicle System</u> - A Complete System That Consists of Multiple Battery Packs To Meet the Overall Vehicle Power Needs. This Includes a Master Controller.

A visualization of this hierarchy is shown in Figure 18.

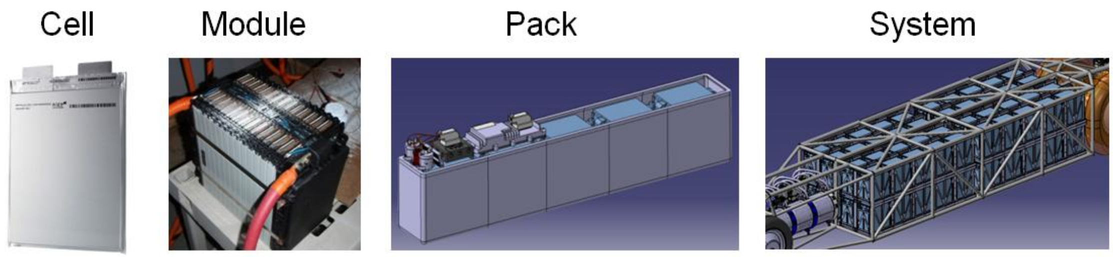

Figure 18: System Hierarchy

2.4 Buckeye Bullet Battery Packs - A Historical Prospective

From the beginning of the program in 1993 to the start of this project, the Buckeye Bullet team has designed, implement, and raced with 5 different drastically different battery packs utilizing 4 different cells, and 3 different chemistries. The history of the packs can been seen in Figure 19 below, in chronological order from right to left.

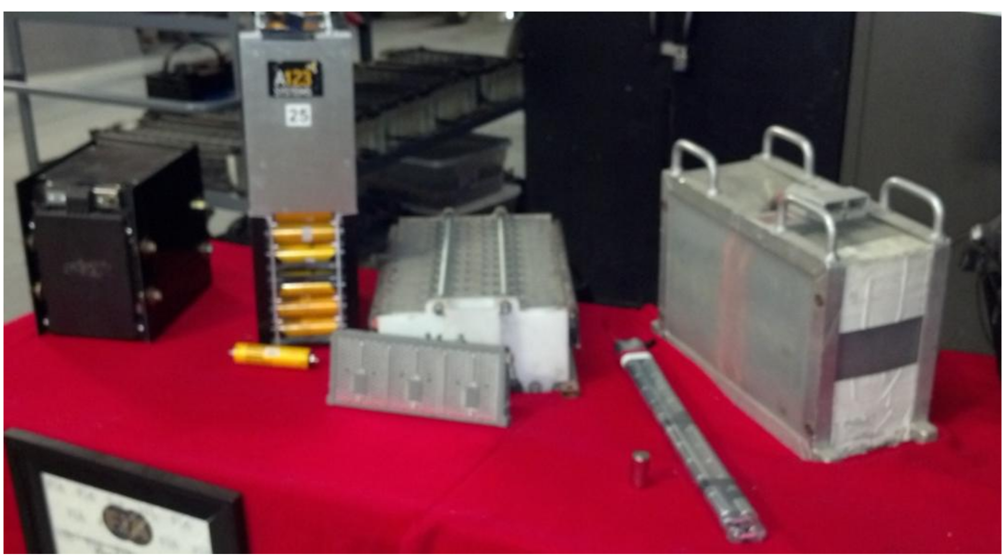

Figure 19: History of OSU EV Racing Battery Packs

The team has had experience with lead acid, NiMH, and Li-ion batteries in cylindrical and prismatic form. The cylindrical Li-ion cells from A123 systems utilized in the Buckeye Bullet 2.5 provided a very useful design and integration experience to help the team learn about modern battery systems before attempting to develop the BB3 pack. In fact the entire BB2.5 program was designed as a test application for the team to gain knowledge and experience in battery systems. A great deal of the data presented in this report relate to the BB2.5 cell testing, and battery pack. Where possible data from the BB3 pack is used, but in many cases this data is still in progress and/or protected by current non-disclosure agreements. Where necessary BB2.5 data is presented as a substitute for the BB3 data. The cell used in the BB2.5 was A123 systems cylindrical 32113 HEV cell, while the cell used in BB3 will be a modified chemistry version of A123's prismatic cell offering. The cells will be referred to from this point forward as either the 32113 or the prismatic cell to distinguish which model is being discussed.

As an interesting aside, an investigation to compare the battery performance over time was completed and the results presented in Figure 20 and Figure 21. Two common metrics to compare battery performance are power density and energy density. This metrics relate the amount of power and energy to either the unit mass (gravimetric efficiency) or volume (volumetric efficiency). It is important to note that the reported power and energy densities are not the absolute maximum for the particular cell, but instead the calculated values based on actual vehicle utilization as implemented.

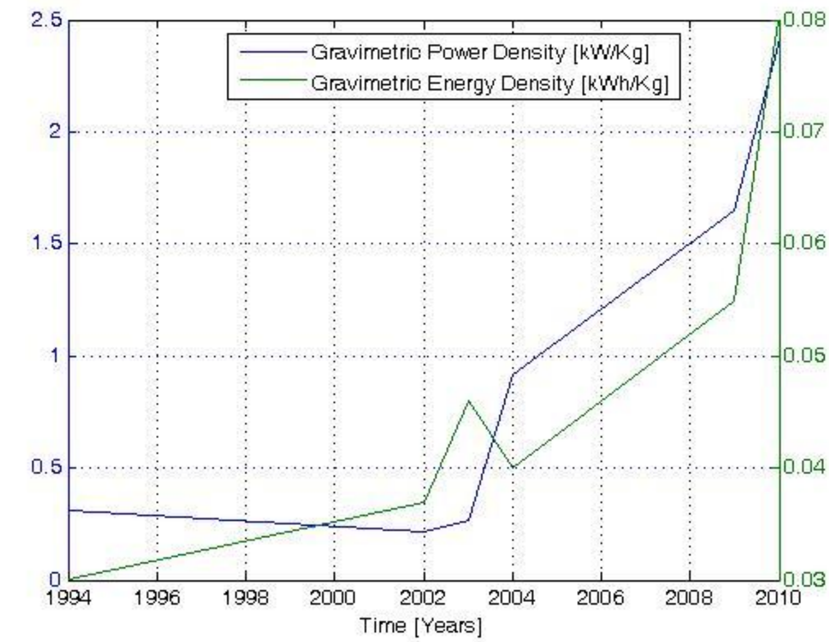

Figure 20: Power and Energy Density (Gravimetric) Over Time

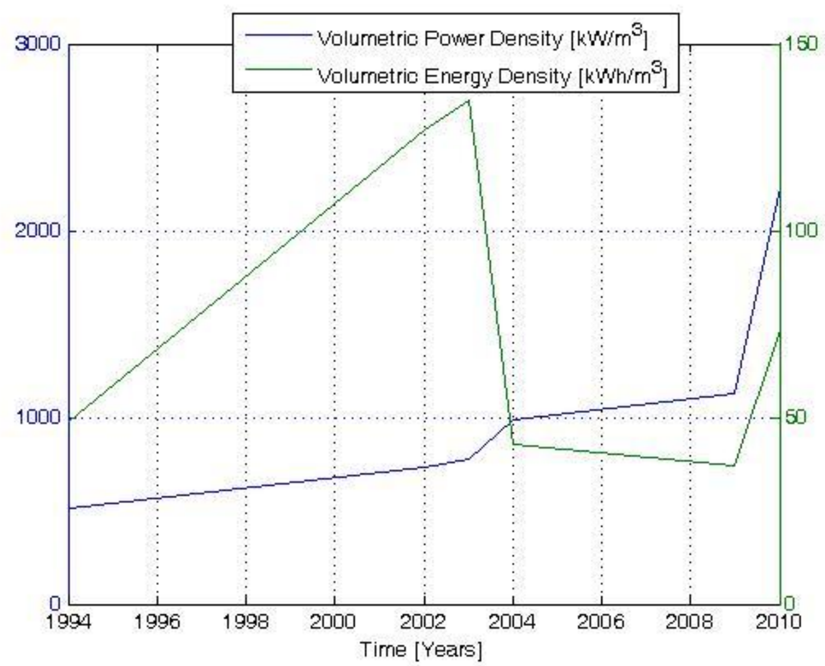

Figure 21: Power and Energy Density (Volumetric) Over Time

The duty cycle of the Buckeye Bullet is full power discharge for 60-80 seconds. This duty cycle is rather unique compared to other vehicles. Because very few batteries can be completely discharged in this time (a 60 C rate), the reality is that by the time the system is designed to meet the power needs there is nearly always enough energy present to meet the vehicle needs. While energy density is in general an important parameter, because of this operating condition, energy density becomes a secondary metric without a real effect on the pack size and weight. The primary metric that leads to overall system size and weight is power density. The previous figures show that the trend for both gravimetric and volumetric power density have increased greatly over time, but the true indicator of the performance potential of BB3 can be seen in the extreme jump in both parameters between the cylindrically packaged BB2.5 back and the prismatic BB3 module. For the same power characteristics, the prismatic packaging offers the team an extreme benefit in terms of system volume and mass, leading to a smaller aerodynamic package, less mass to accelerate, and overall a much faster vehicle.

Chapter 3: Battery Testing

3.1 Types of Test

The design of a battery system begins with fully understanding the capabilities and limits of the selected battery technology at the cell level. A full development program requires cell characterization and validation at the module, pack, and system levels. While a full research program might be interested in a wide ranges of test over a vast range of operation conditions, but Bullet program can somewhat simplify testing by narrowing the scope to the specific operation conditions of Bonneville racing. There is little point in investigating the effects of cell aging, cold temperature operations, and low discharge current performance curves. In reality the Bullet will have an extremely low number of cycles over its life, always be extremely hot environments, and always be pulling high levels of current. There are however still a large number of tests required to really characterize a battery, even under these limited operating conditions.

The relevant test to our program include:

- Capacity Testing
- Hybrid Pulse Power Characterization Testing (HPPC)
- Racing Power Profile Testing
- Thermal Testing

Capacity testing allows the actual cell capacity to be compared to the manufacturers claim, and gives some indication to the age and health of the battery. While it is not critical for the Bullet program, a capacity result that deviates highly from other similar cells can quickly indicate a problem. The HPPC test is a standardized test that allows characteristic necessary for battery modeling to be determined experimentally. This will be discussed further in the following sections and in Chapter 6. The two test most relevant to the program are the race power profile testing and various thermal testing exercises. In the power profile tests, the cells are run through the exact current request cycle that will be seen in the race vehicle as determined by the motor needs. This test is the most representative of what to expect in actual operation. As discussed in Chapter 1, the thermal operation conditions are extremely important to the actual cell performance. A matrix of tests related to thermal performance are performed to determine the cooling strategy needed, optimum starting temperature, and understand the failure potentials of the pack if a race doesn't go according to plan.

3.2 Experimental Setup and Procedures

The OSU Center for Automotive research which houses the Buckeye Bullet program has extensive battery testing capabilities and equipment. All of the testing for this program is completed in the OSU-CAR labs under the advisement of the OSU CAR staff. Recently lab a dedicated to student projects battery testing has been donated by Denso Corporation and we are excited to utilize this equipment in the future. In general all testing takes place on some form of battery cycling setup. A cycler consists of a power supply and a resistive load, or a "charger" and a "discharger". Both the supply and load are computer controlled allowing for specific charge and discharge profiles to be completed. The labs are setup for 24 hour testing, so extended tests and high cycle numbers are not a problem. The cyclers range in size from 3.3 kW cell stations to 500kW pack stations. Six of the cell cycle stations as well as a close up of the 3.3 kW supply and load are shown in Figure 22.

Figure 22: Battery Testing Equipment

While Cylindrical cells are structurally self supporting and provide the necessary compression during operation, prismatic cells cannot function as standalone pouches. The must either be compressed in packs, or placed in individual compression fixtures as shown in Figure 23.

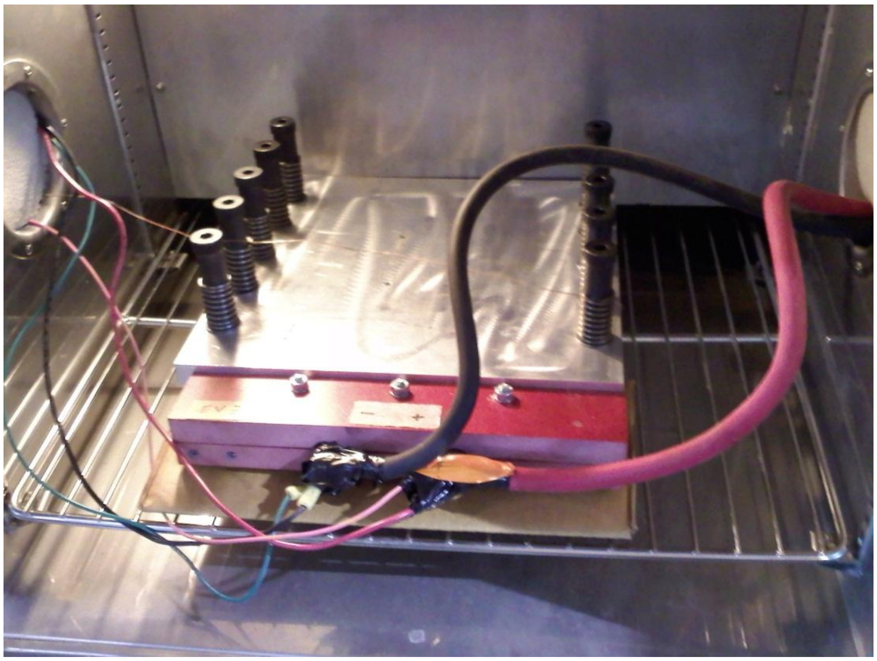

Figure 23: Cell Compression Test Fixture

Thermal testing can be accomplished in one of two ways. At the cell level thermal devices can be attached directly to the cell to control temperature. Is common to place prismatic or cylindrical cells in an aluminum fixture similar to the one shown above, and to attached an electro-thermal device called a Peltier junctions to control the temperature. Another option for larger modules or packs is to place the entire system in a device called an environmental chamber as shown in Figure 24. The environmental chamber can hold a very wide range of temperatures quite accurately and has the option of also performing humidity control.

Figure 24: Environmental (Thermal Control) Chamber

3.3 Power Testing

As discussed above the first test is the capacity test. The discharge profile is shown in Figure 25. The cell is discharged to a specified voltage which is designated as the minimum voltage by the manufacturer. The current and discharge time are closely monitored and from this the amp-hour rating can be determined. This test is repeated multiple times and the results are averaged to produce an actual capacity rating.

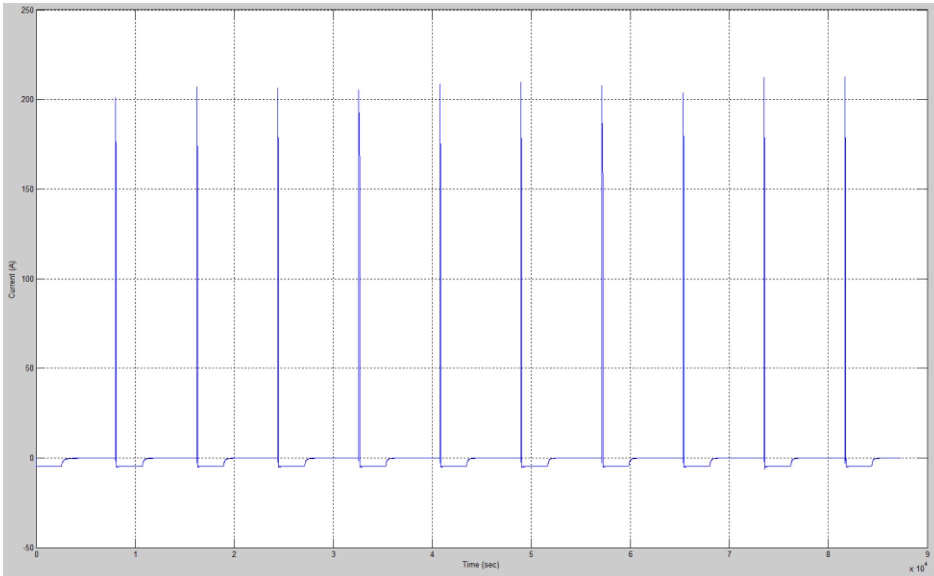

Figure 25: Capacity Test

The next test of interest is the HPPC (hybrid pulse power characterization test). The discharge profile is shown in Figure 26 below. The test parameters are standardized and completed as suggested in the Freedom Car Manuel. This cycle involves very specific calculated charge and discharge rates which step incrementally in time. The test measures the cells ability to deliver pulses of power at different operation conditions across the state of charge. The test has been set up to help determine the experimental coefficients of the battery resistance and capacitance to be used in modeling exercises. This concept will be further investigated in Chapter 6.

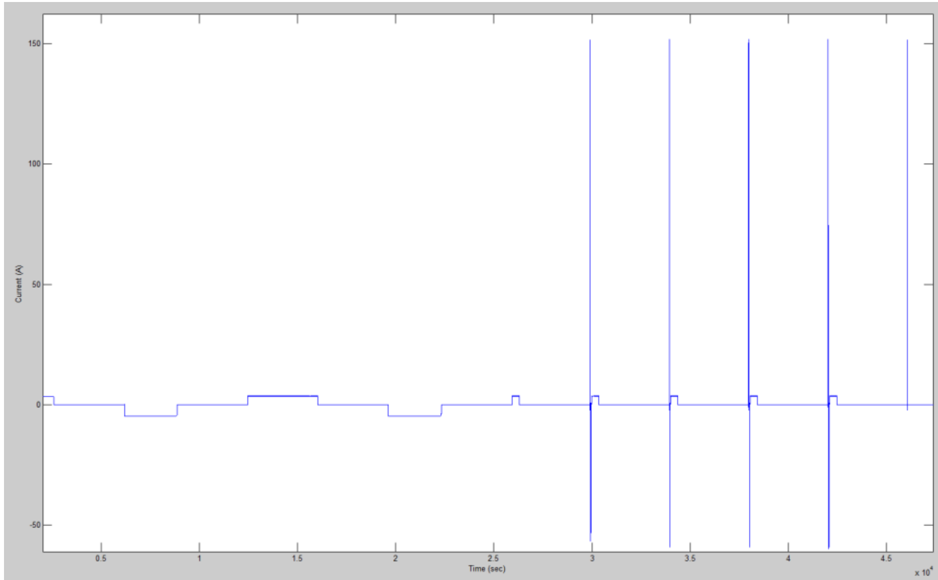

Figure 26: FreedomCar HPPC Test

With the initial capacity and HPPC test completed the next step is to look at the cells specific response to the Buckeye Bullet power cycle. As previously introduced discharge rates are reported at C rates. For a cell to be effective for use in the Buckeye Bullet it needs to be able to be deliver all of its energy relatively quickly. A cell capable of a 30 C rate is preferred, meaning it can deliver all of its energy in two minutes. A cell with a lower maximum C rate results in carrying extra energy and thus mass on board the vehicle. When performing power test, a maximum C rate is determined in consultation with the manufacturer, and then the test matrix shown in Figure 27 implemented. The program involves testing at 1/3, 2/3, and full discharge rates. The time to discharge for each of these test can be seen in the Figure.

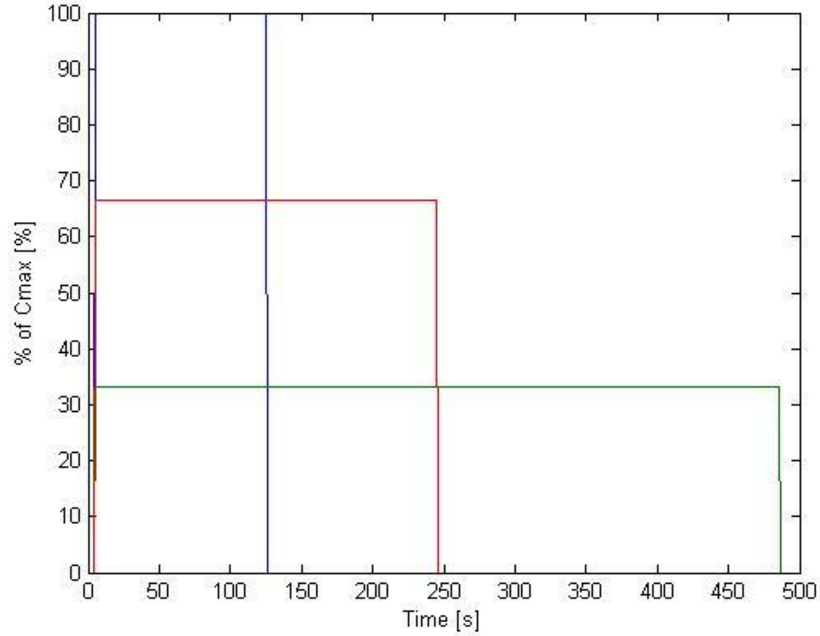

Figure 27: Race Profile Test Matrix

In the case of the BB2.5, a multi speed transmission was used, so the motor current demand involved a segments in each gear as seen in Figure 28. When this current profile was applied to the BB2.5 32113 cell the resulting voltage profile becomes the output of interest. This profile can be seen in Figure 29. The current profile is followed exactly, but the voltage changes as a result of current, change in rate of current, and temperature. The motor performance is ultimately dictated by power delivery which is a function of both the current requested and the resulting voltage. From this prospective the current is considered a known input and the voltage response is the parameter that is actively monitored and studied.

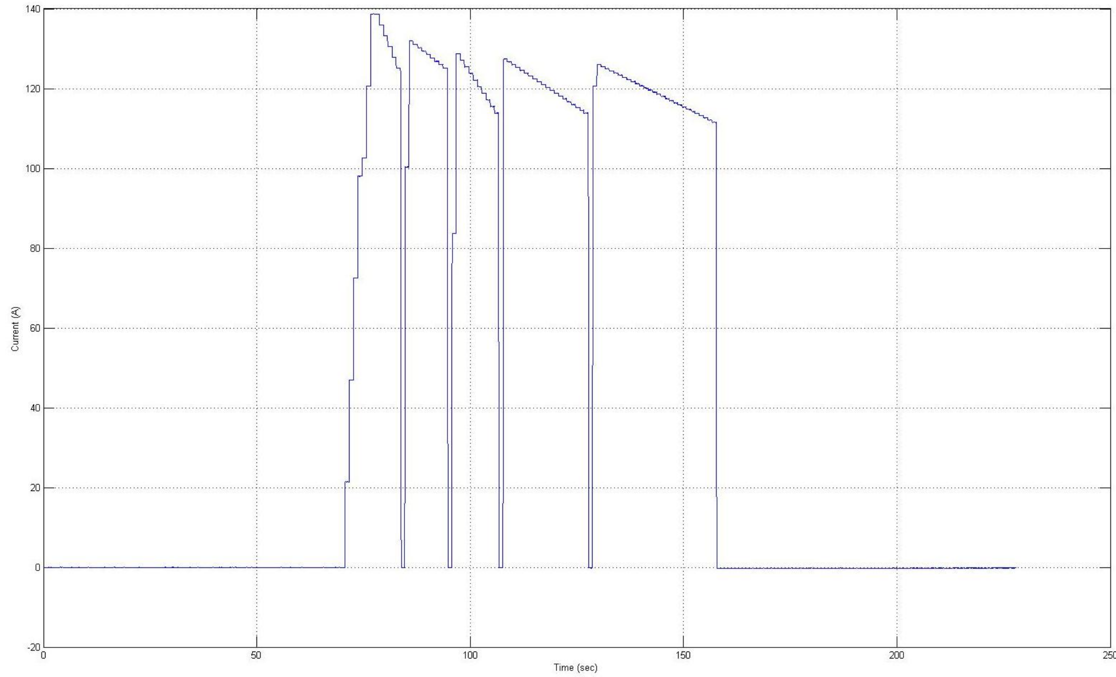

Figure 28: BB2.5 Race Profile - Current Draw

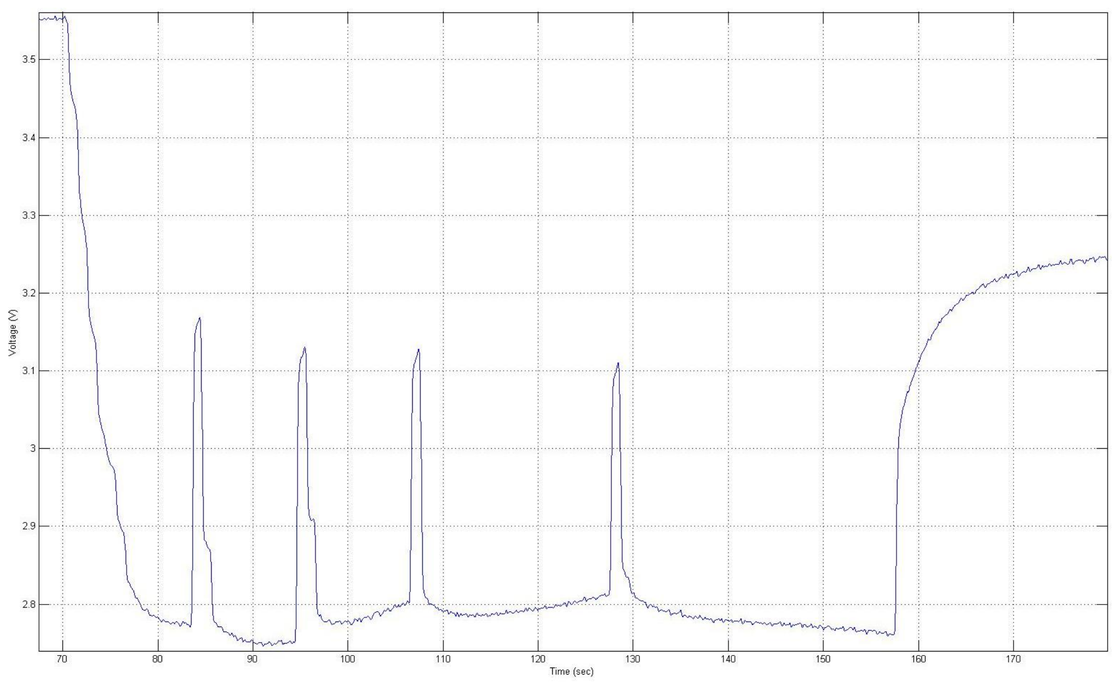

Figure 29: BB2.5 Race Profile - Voltage Performance

To demonstrate the difference in cell chemistry and form factor, two different A123 Systems products were tested using the same BB2.5 power cycle. The results are shown in Figure 30. The 26650 is a more energy driven cell targeted to application such as the long range electric vehicle market. The 32113 is the power driven cell which was developed for pulse power applications such as the hybrid vehicle market.

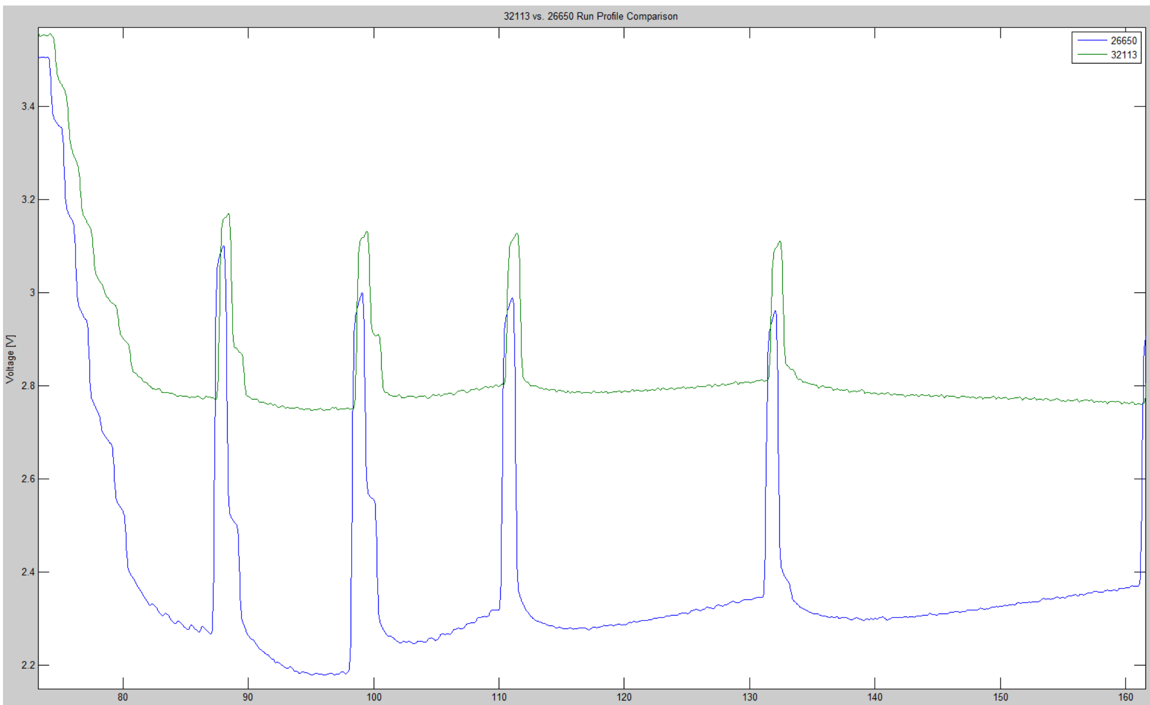

Figure 30: BB2.5 Race Profile - Voltage Performance Between 2 Different Cell Models

The power cell maintained a voltage of approximately 2.8 V under load while the energy cell dropped to 2.3V. For a pack sized for a 900V open circuit fully charged voltage this means the voltage under load would drop to 700 V for the power pack but only 575 V for the energy pack. In this case the minimum acceptable voltage is 680 V so the power cell made the cut but the energy cell did not. More energy cells could be added in series, but this would take the open circuit voltage above 900 V, which is unfortunately the maximum acceptable voltage of the inverter. In this case this led to the decision that this cell was not a good fit for the program. While some more exotic solutions such as adding series elements and then starting at a less than 100% SOC could allow the cell to be used, it is not an necessary effort when there are better cells for the application available.

Another example of defining an optimized system is matching the cell form factor and capacity to the application. While a superior chemistry in terms of voltage response, power delivery, and reliability is very important, nearly equally important is the ability to match the needed capacity to the application. During the initial cell selection phase the team investigated many different cells. In each case a maximum C rate was established and the cell was tested at that rate. If the voltage dropped too low to deliver proper power to the motor, then the C rate was decreased. Decreasing the acceptable C rate specification effectively means adding parallel components to the pack. In the case of a small form factor cell this might may not have a large effect on the system size and weight, but in a larger form factor cell that was only being used in a 1P configuration this might mean doubling the size and weight of the pack. This precise issue came up with one of the A123 competitor cells investigated. In this case it was a large form factor prismatic cell. On paper, a four parallel elements provided enough power and energy to meet the needs of the BB2.5 race vehicle. When the manufacturers specifications for both the competitor cell and A123's 32113 were considered, the system described in

Table 2 were established as system parameters and requirements. It can be seen that based on the manufacturers specifications, the packs would result in similar size and volume with a slight advantage to A123, but the competitor pack contained more than twice the energy. This indicated that the vehicle might be able to complete two runs without recharging which could be a trade off worth the slight increase in volume and mass.

Table 2: Sample Pack Sizing Comparison for BB2.5 - Manufacturer Specs

Parameter	Competitor	A123 32113
Nominal Voltage/Cell	3.65V	3.6V
Nominal Capacity	16Ah	4.4Ah
Weight/Cell	450g	225g
Maximum Pack Voltage (No Load)	900V	900V
Minimum Pack Voltage (Under Load)	730V	730V
Current/Cell Maximum Requested	213A	121A
Used kWHrs/run for Pack	~13.5kWHrs	~13.5kWHrs
Nominal kWHrs/Pack	~52kWHrs	~25kWHrs
Used Ah/run for Pack	~17Ah	~17Ah
Nominal Ah/Pack	64Ah	30.8Ah
Series Cells/Pack	245	275
Parallel Cells/Pack	4	7
Total Cells/Pack	980	1925
Pack Volume (Batteries Alone)	.252m^3	.191m^3
Pack Weight (Batteries Alone)	441kg	433kg

Next came power testing and verification. Power cycles showed that the 32113 pack could actually be reduced by one parallel element and several series elements while still meeting the system requirements. The competitor cell on the other hand made it through the first portion of the test very well, but during the discharge that equates to fifth and final gear the voltage crashed as seen in Figure 31. This meant that the to increase the end of run voltage under load, an additional parallel element had to be added. The final specifications for the packs after considering the testing data are shown in Table 3 below.

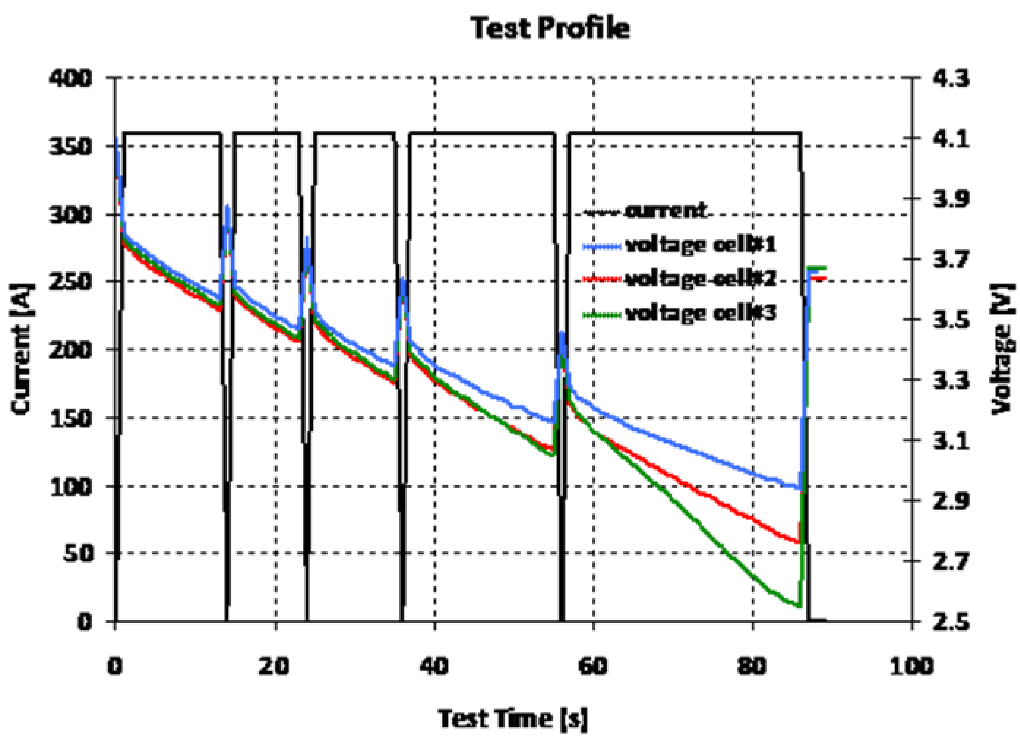

Figure 31: Competitor Cell Race Profile Voltage Performance

Table 3: Sample Pack Sizing Comparison for BB2.5 - After Testing

Parameter	Competitor	A123 32113
Nominal Voltage/Cell	3.65V	3.6V
Nominal Capacity	16Ah	4.4Ah
Weight/Cell	450g	225g
Maximum Pack Voltage (No Load)	900V	900V
Minimum Pack Voltage (Under Load)	750V	700V
Current/Cell Maximum Requested	170A	141A
Used kWHrs/run for Pack	~13.5kWHrs	~13.5kWHrs
Nominal kWHrs/Pack	~65kWHrs	~21.4kWHrs
Used Ah/run for Pack	~17Ah	~17Ah
Nominal Ah/Pack	80Ah	26.6Ah
Series Cells/Pack	245	250
Parallel Cells/Pack	5	6
Total Cells/Pack	1225	1500
Pack Volume (Batteries Alone)	.315m^3	.149m^3
Pack Weight (Batteries Alone)	551kg	337kg

When the actual needs are updated to reflect the testing data, the two packs that initially seemed to be quite comparable in terms of volume and mass became drastically different. The competitor pack is more than twice the volume and more than 60% heavier. The competitor pack also forces the vehicle to carry along more than four time times the required energy. With this exercise in mind, the concept of matching a cell both in terms of absolute performance and appropriate size to the specific application, becomes quite clear.

The Buckeye Bullet 3 team proposed that the motor used in the BB3 would not require a multi speed gearbox. This changed the drive cycle and thus current request required for BB3 power testing. A sample BB3 race profile test is shown below. Figure 32 shows the current profile of the test and Figure 33 shows the resulting voltage response. The current profile is now a literary increasing ramp during the constant torque period of the motor and a flat current request during the constant power region of the motor. The trend of increasing voltage during the flat portion of the current request can be best explained by the increase in operation temperature during the run.

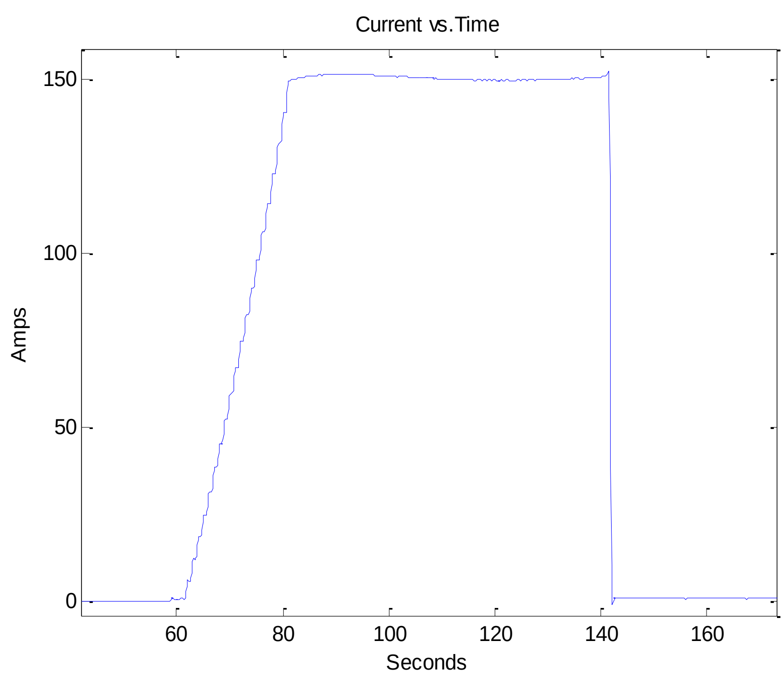

Figure 32: BB3 Race Profile - Current Request

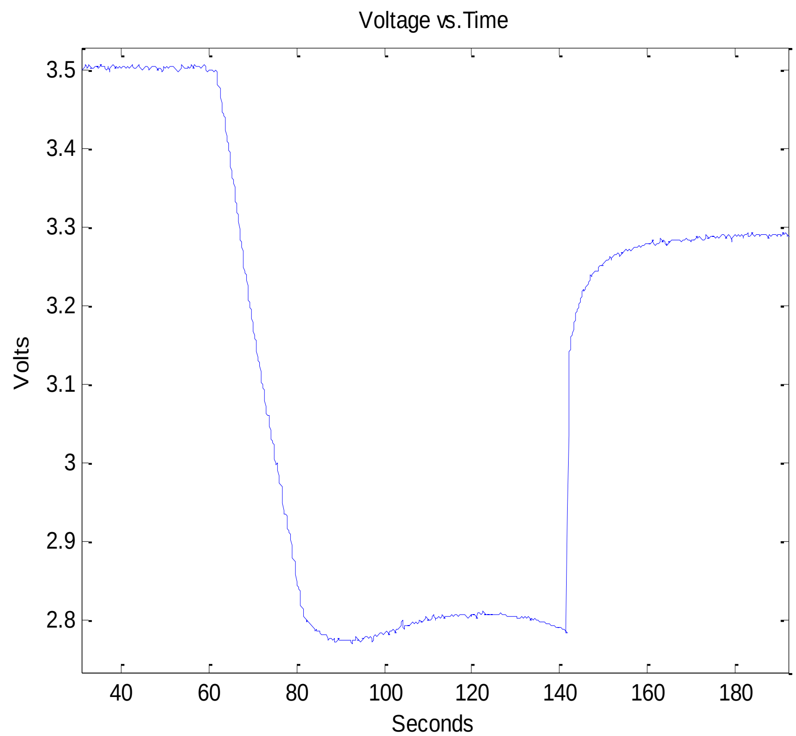

Figure 33: BB3 Race Profile - Voltage Performance

3.4 Thermal Testing

With the power needs of the system specified and a proposal for a series and parallel configuration of the pack based on scaled cell testing data, the next major consideration is thermal strategy. In the simplest terms the harder the cells are pushed the more they will heat up. To some degree heat is a performance enhancement, but only to a very hard limit. Heat very quickly transitions from voltage booster to a cell destroyer. Depending on the exact operating conditions the thermal needs can vary from no cooling needed at all, to a requirement very complex actively managed liquid cooling system. When considering the thermal system design, the following concepts were carefully considered:

- Cooling Capacity Need - What if any cooling will be needed?
- Cooing Strategy - What type of cooling system best meets systems needs?
- Pre Heating - is beginning at an elevated temperature worth the effort and risk?
- Regenerative Braking - if used what thermal effects does it have on the system?

Each of these questions can be answered by performing thermal characterization of the battery in much the same way that a power characterization was performed in the previous section. The main difference thermally motivated testing is that in most cases the testing cannot simply be performed at the cell level and scaled. As should be expected, the thermal tests are heavily influenced factors such as cell proximity to one another, air gap, packaging materials, bus bar materials, and ambient conditions.

When considering the cooling strategy to implement there are many options including:

- Natural Free Convection
- Forced Air Convection
- Liquid Cooling with Cold Plates
- Submersion Cooling
- Expanded Gas Cooling

In the context of a race car the most efficient system would have no onboard components that add volume and mass to the car. This leads to the concept that in the ideal case either the batteries would be sized such that the duty cycle did not produce enough heat to require cooling, or that a system that could be kept completely off board and used between runs to condition the batteries.

All of the testing in the following section represents the thermal analysis of a BB2.5 racing cycle. The first case studied was the affect of initial temperature on system performance.   Figure 34 shows the voltage profile for two different initial temperatures, one at 25 degrees Celsius and the other at 45 degrees. It can be seen that the high initial temperature leads to more than 200 mV increase per cell over the entire run. In a 250S pack this means a 50V increase in the bus voltage. The penalty is obviously the elevated end of run temperature, which means more cooling is needed to prepare for the next run.

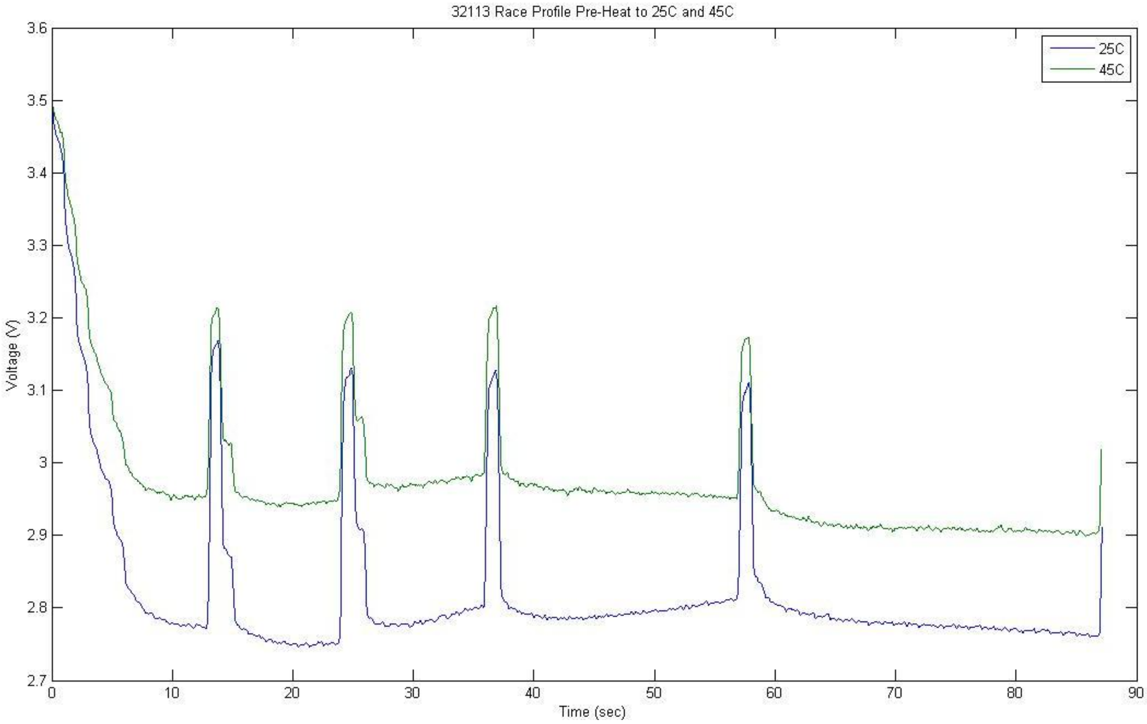

Figure 34: Affect of Preheating on Voltage Performance

When attempting to select a cooling strategy the main question is how much cooling capacity is really needed. In the context of the Bonneville record attempt the true need is to perform two race cycles within a one hour period. To begin to understand at least the magnitude of cooling needed two tests were performed. First the best case free convection scenario was tested by allowing a single module to sit in unobstructed ambient air during several racing cycles. An initial temperature of approximately 25 degrees Celsius was utilized. Based on previous tests it was determined that that maximum safe starting temperature was 45 degrees Celsius. The pack was put through a race cycle and then charged for an hour and then the process was repeated as many times as possible until the initial starting temperature for the run exceed the maximum start temperature. The results of this test can be seen in Figure 35. More than 5 runs were successfully completed. This shows that if the modules were in fact sitting in open air then no cooling system would be needed at all to achieve two consecutive races without thermal concern. Next the test was repeated, but for the worst case scenario of a completely insulated module. This simulated modules tightly packed in the race vehicle with no access to ambient air. The results of this test can be seen in Figure 36. In this case two runs could be completed back to back but a third run could not be completed until a several hour rest period allowed the cells to cool to the maximum run start temperature. At the time of this testing the actual cell to be used in the BB3 was not available for testing, so this data is based on scaled testing with a similar product.

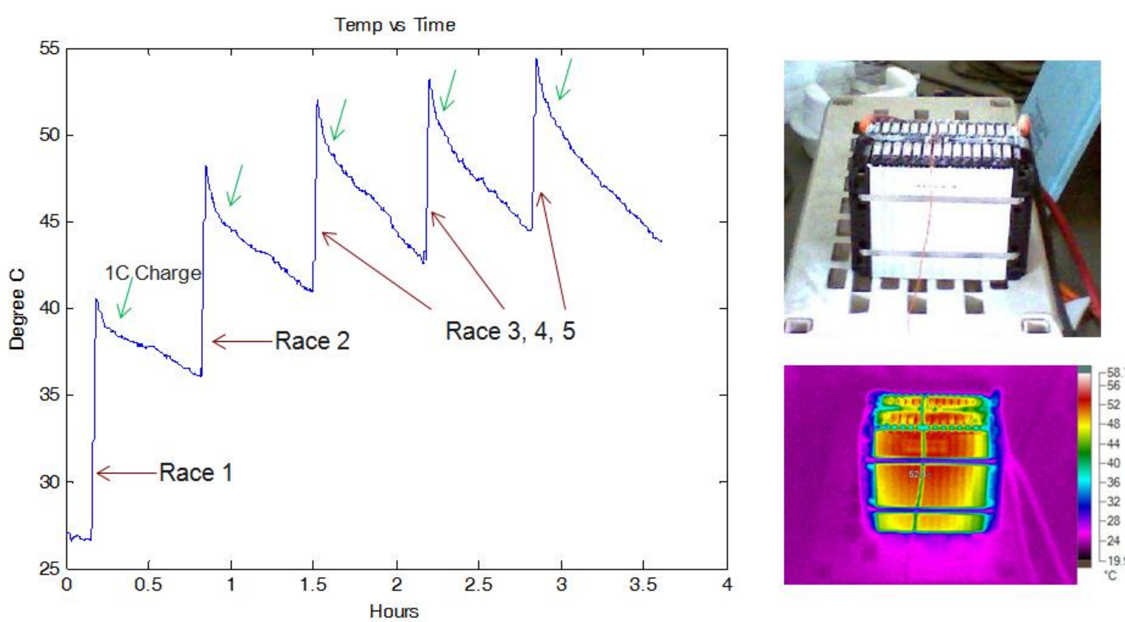

Figure 35: Thermal Performance During Racing Profile - Non-Insulated Case

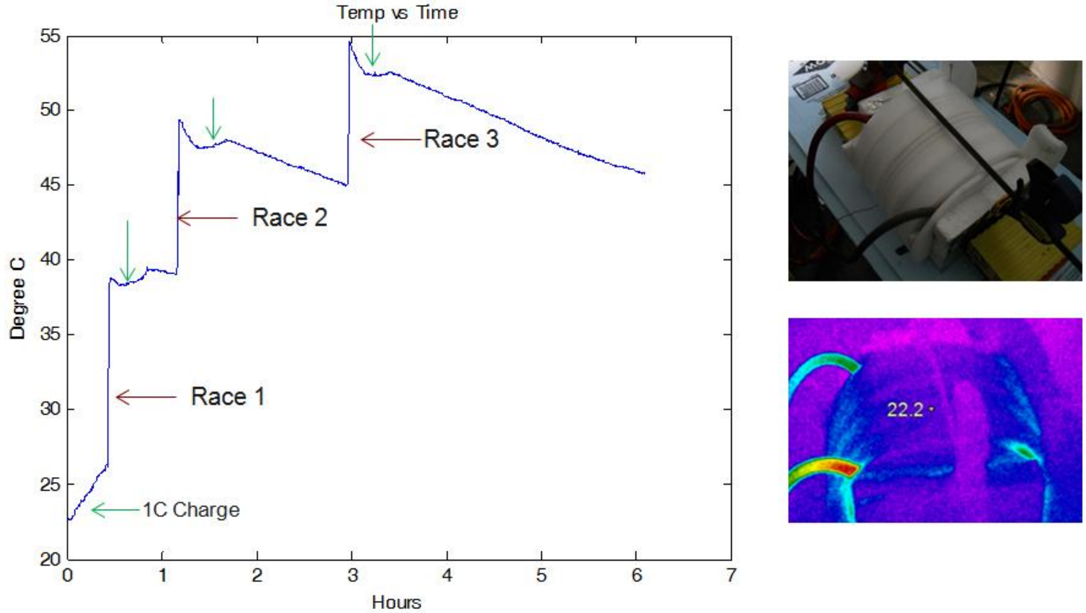

Figure 36: Thermal Performance During Racing Profile - Insulated Case

The results of this test lead to the conclusion that on board vehicle active cooling would probably not be needed, but it would be necessary to remove heat from the system during the pit stop. Because the testing was based on scaled performance and not the actual cell to be used, it was initially decided to plan on the conservative side and develop a liquid cooling system that would be in place on board, but with the cooling agent and prime mover off board. During a pit stop a cold water supply would be connected to the vehicle and cycled. At a later date when the actual cell was available for testing, the results showed that the real cell preformed better than expected and even in the completely insulated case 3 racing runs could be performed without thermal issue. This data is omitted from the report due to non disclosure issues, but was instrumental in the final cooling strategy decision presented in the next section.

Another interesting consideration is the amount of time it take the heat to be generated and then to propagate to the outside of the cell. Even though current is being delivered at a high rate for approximately 80 seconds it is not until after the run that the cells start to heat up in their core, and often it is not until several minutes after the run that the maximum temperature is seen at the outside of the cell. This phenomenon is shown in Figure 37 below.

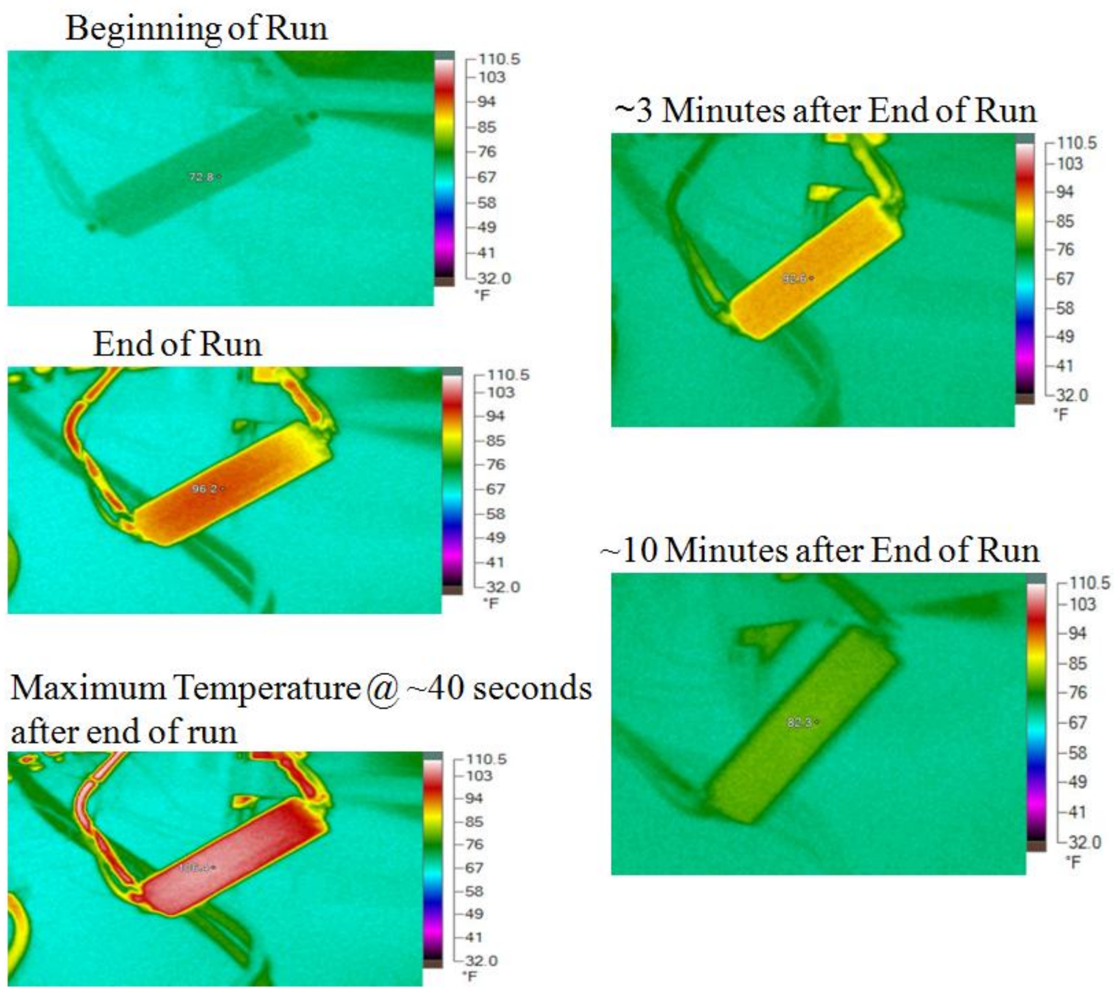

Figure 37: Heat Generation and Transfer Rate

The final thermal consideration tested was the bus bar temperature. While the rated operating temperatures are around 50 degrees Celsius in a short term racing application it is acceptable to push the maximum temperature closer to the ultimate failure temperature of 85 degrees Celsius. At high current rates the cells did not exhibit any thermal problems, but the copper bus bars also heat significantly from the resistive losses of the power they are carrying. At very high current rates the bus bars actually reach temperatures significantly higher than the cells. At the current proposed operating conditions this is not a problem, but if any more current is required form the powertrain a bus bar cooling solution will have to be investigated as the bus bars will begin to reject heat into the cell and cause the cells to fail. The bus bars are difficult to access making forced convection difficult, there are many of them meaning the system would be large and complex, and they are conductive so any tradition all liquid cooling methods will not work. It is the sincere hope of the designers that this does not become a need as such a system brings up these significant design challenges. Thermal images of bus bar testing are shown in Figure 38 and Figure 39. It should be noted that in a lithium cell the anode and cathode terminals are made of different materials (usually one aluminum and one steel) with different heat transfer properties. This causes significant temperature differences between the two terminals as seen in Figure 39.

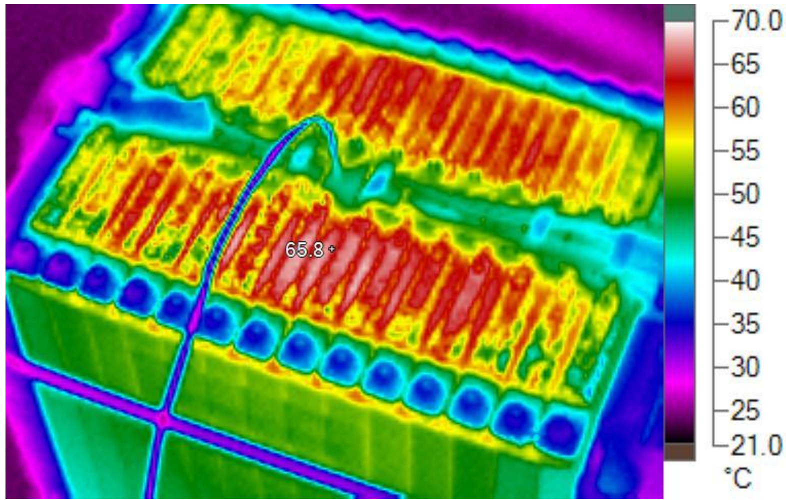

Figure 38: Thermal Profile Of Electrical Bus Bars - Module

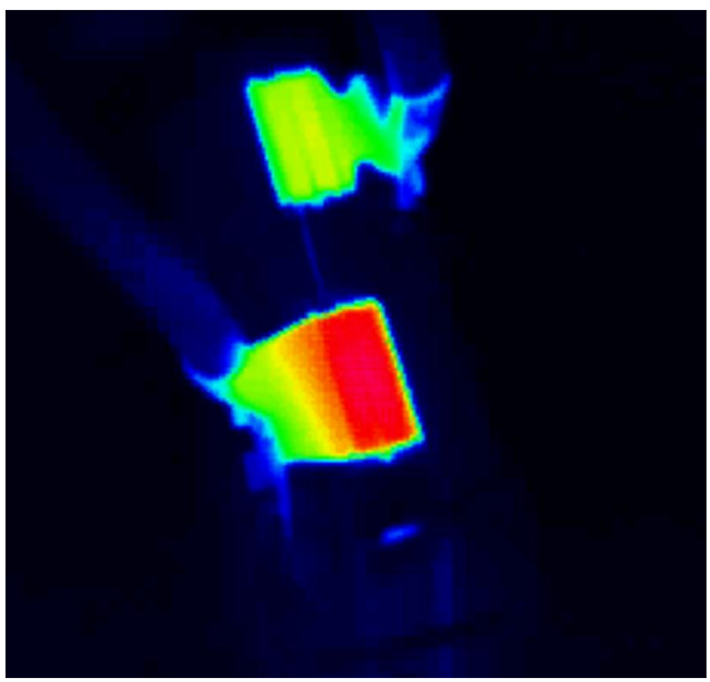

Figure 39: Thermal Profile of Electrical Bus Bars - Cell

3.5 Proposed Pack Specifications

With the information reported in the sections above the battery system architecture and thermal strategies were determined. The powertrain configuration includes eight inverters, so the race profile testing described was based around the matching one battery pack to each inverter. The each pack was set up as a 250S - 1P systems with eight packs in the vehicle. This architecture is summarized in Figure 40.

Figure 40: Proposed Battery System Architecture

As described above it was determined that the cooling requirements of the system order to perform two runs within a one hour period were minimal. As such it was determined to forgo an active cooling system, and simply leave provisions in the mechanical packaging for airflow around the modules. It was proposed that a simple solution to provide a large quantity of cold air for forced induction would be to utilize a refrigeration unit from a semi truck refrigerated trailer or "refer unit" as shown in Figure 41. This system is completely self contained, operates at temperatures as low as -20 C which align with the battery capabilities, offers an appropriate flow rate, and can easily be powered with the on board diesel generator at the most remote locations including the salt flats.

Figure 41: Proposed Cooling Prime Mover

Chapter 4: Safety System Design and Component Selection

4.1 Safety Considerations

The primary goal, design parameter, and focus of the Buckeye Bullet program is safety. The lives and wellbeing of the students, staff, and by-standers is of the utmost importance, and additionally as the ambassadors for new automotive technology to the public, it is critically that all vehicle systems operate safely and without incident. When designing and analyzing the system from a safety perspective the following levels of safely and additional situational scenarios were considered:

- Chemistry Safety
- Cell Level Monitoring Safety
- Module / System Level Monitoring and Control Safety
- External Control System Safety
- Internal Pack Protection
- External Pack Protection
- Charger System Design and Safety Considerations
- First Responder Training and Safety
- Shop Safety
- Transportation Considerations

4.2 Pack Protection

The first level of pack protection comes from selection a stable battery chemistry with an excellent monitoring and control system. Proper implementation of supervisory controls can and should prevent all battery incidents, long before there is a notable problem. Schematics of the power and control systems are shown in Figure 42. Safety devices in the power loop is the topic of the next section, but for now the control systems will be explored.

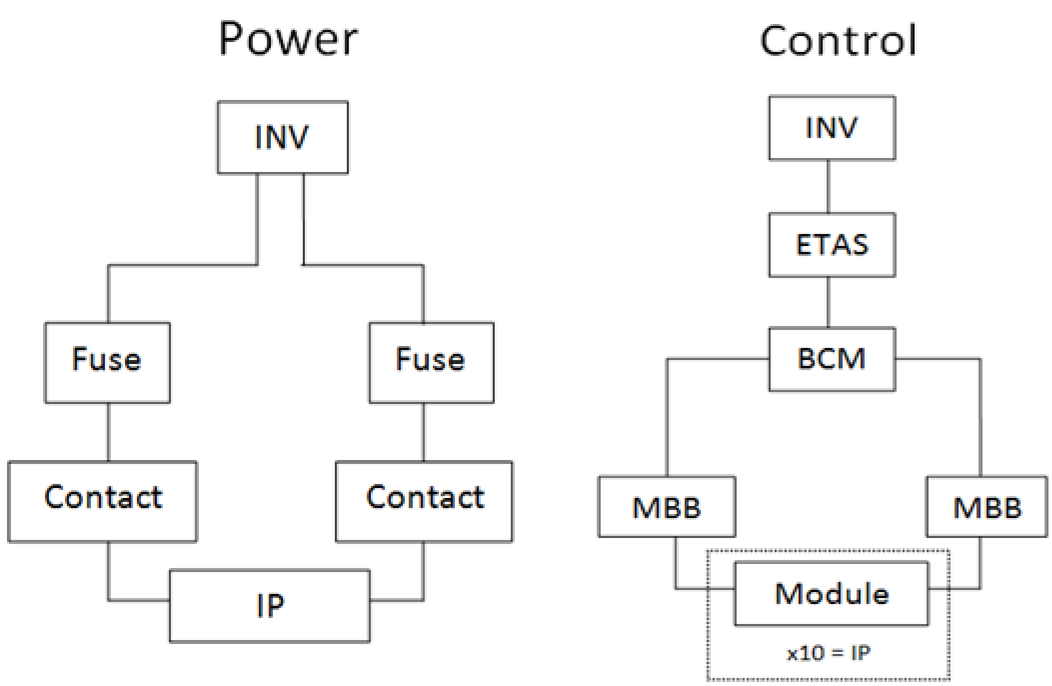

Figure 42: Pack Protection Concept Schematic

4.2.1 Safety At The Cell Level

The first level of pack protection comes from the inherent safety of the battery chemistry. Aside from the excellent power and thermal characterizes one of the driving forces behind selection the A123 systems battery was the safety and stability of their iron nano-phosphate chemistry. When compared to the common metal-oxide lithium battery variants, iron-phosphate batteries are extremely safe. The primary reason for this is that the reaction that takes place in metal-oxide batteries requires the presence of an excess of lithium ions. Under normal operation this is not a problem, but in the event of overcharging too much lithium can propagate to the anode and actually cause a build-up of unstable lithium metal, a phenomenon known as lithium plating. When lithium plating occurs the metal itself begins to burn and leads to nearly uncontrollable thermal runaways. With iron-phosphate chemistry there is no excess lithium so this simply cannot happen. The cells can be forced over temperature an vent their electrolyte, but the can never reach the thermal runaway state that are seen as a result of lithium plating. The simultaneously amazing and scary aspect of the thermal run away characteristics is how quickly they can happen. Figure 43 shows the rate of change in temperature as different cell chemistries are heated. Without zooming in the A123 chemistry appears to be a complete flat line at zero degrees. In fact when the A123 cells reach failure from overcharging they spike at a rate of 20 degrees C per minute, a very controllable condition. Metal oxide batteries on the other hand can spike at rates of more than 1800 C per minute under thermal runaway conditions. The buffer of safety in chemistry adds a great deal of comfort to the BB3 battery system.

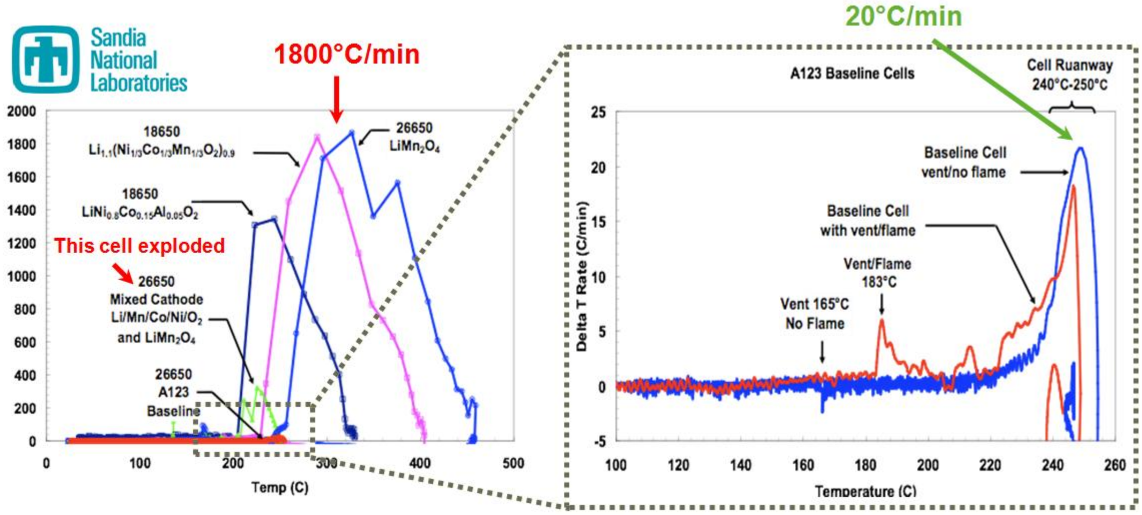

Figure 43: Thermal Runaway Characteristics of Li-Ion Batteries (Courtesy of A123 Systems)

4.2.2 Battery Control System Safety

The next level of system protection is the various control systems on board the battery pack and the race vehicle. The battery pack itself as a complete battery management system. This system is made up of several pieces of hardware that perform specific functions to ensure the safety of operation of the pack. The overall system is referred to as the battery management system or BMS. The first component of the BMS is the MBB or module balancing board. This board measure the voltage at every series connection and the temperature of each module. The data is reported over a CAN network to the battery control module or BCM. The BCM interprets the data from all of the modules and takes corrective action when a problem is detected. The BCM overseas the electrical control devices found in the EDM or electrical distribution module. This includes the contactors that open and close to control the ability of the pack to output power and the pre-charge circuit. Contactors will be covered further in the next section. The pre-charge circuit allows the battery pack to first be exposed to a high resistance limiting the current draw to ensure there are no ground faults downstream of the pack. If the correct operating conditions are met then the pre-charge circuit is bypassed and full pack current is allowed to flow. The final BMS module is the current sensing module or CSM. The CSM measures the pack output current and reports it back to the BCM. This allows the BCM to calculate expected operating parameters based on the amount of power being produced. The BMS is an incredibly well designed and reliable system, but there are a few potential failure methods. Most are non catastrophic and would simple lead to an unwanted system shutdown. The one really catastrophic failure that can occur is if the system attempts to shut down and open the contactors but due to high current the contactors weld shut keeping power flowing. The battery module including the MBB boards and connection is shown in Figure 44.

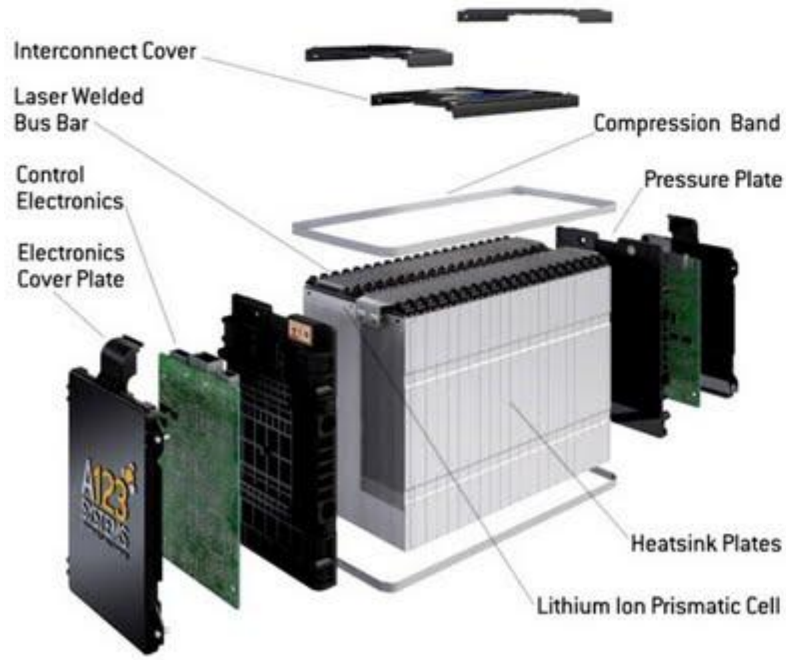

Figure 44: A123 Battery Module Design (Courtesy of A123 Systems)

The next level of control safety is the overall vehicle controller. This controller is constantly passing requests on to the battery pack and interpreting data from the battery pack. If the vehicle control is encountered with a scenario that is not acceptable it has the ability to both requires a shutdown of the pack through the BMS, as well as the ability to open the second set of contactors downstream at the inverter level.

4.2.3 Discrete Safety Devices

In addition to control level decisions that end in the ability to open contactors, discrete mechanical links are needed to ensure system safety under contactor failure. The primary means of doing this is with conventional fuse technology. The design of a fuse is such that a calibrated wire is packaged in a sand casing. The wire is designed to break from thermal failure corresponding to a particular current/time relationship. While under normal conditions a BB3 battery pack will only draw a maximum of about 400 amps, the extremely low internal resistance of the batteries leads to the potential of more than 5000 amps of current draw under shot circuit conditions. The battery fuse and contactor schematic is shown in Figure 45.

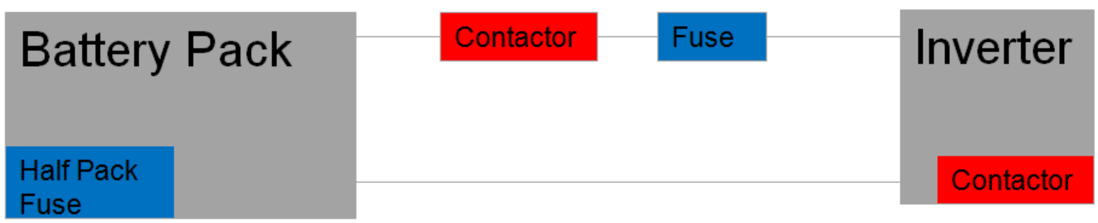

Figure 45: Pack Protection Schematic

4.2.4 Manual Service Disconnect

The manual service disconnect is a device that allows the high voltage loop to be mechanically divided. The allows the packs and thus the vehicles to be mechanically disabled ensuring that the vehicle cannot be operated and no electrical power can leave the batteries. This mode is ideal for service, transportation, and trade show type events.

4.3 Component Testing and Specifications

While it is true that every electrical device from fuses to contractors, to wiring comes with a specification sheet, it is not universally true that the specified ratings are appropriate for every application. The NEMA type ratings supplied are for continuous operation in industrial and commercial settings. If the BB3 electrical components were sized for the industrial ratings, there would be more weigh and volume consumed by power wiring than there is in the entire electrical driveline. It is of critical important to test each of the system components under racing conditions and establish 2 minute duty cycle ratings to define the appropriate devices. The following sections describe the testing and selection of fuses, wiring, contactors, and connectors.

4.3.1 Fuse Selection

Fuses are arguably the most difficult device to specify in the BB3 application. There are two considerations when selection a fuse. First is should not fail under normal operating conditions and second it should fail at a reasonable threshold. A fuse could be sized to never fail under normal operation, but in effect also never fail at elevated problematic current levels. In contrast an undersized fuse could fail during normal operation ruining a record attempt. The fuse manufactures supply very detail performance that specify the current vs time to fail for each fuse model. If these curves were complete this would be very useful data, but in reality the BB3 operating conditions always fall in the "imaginary" linearly extrapolated region such as is sown by the green trace in Figure 46.

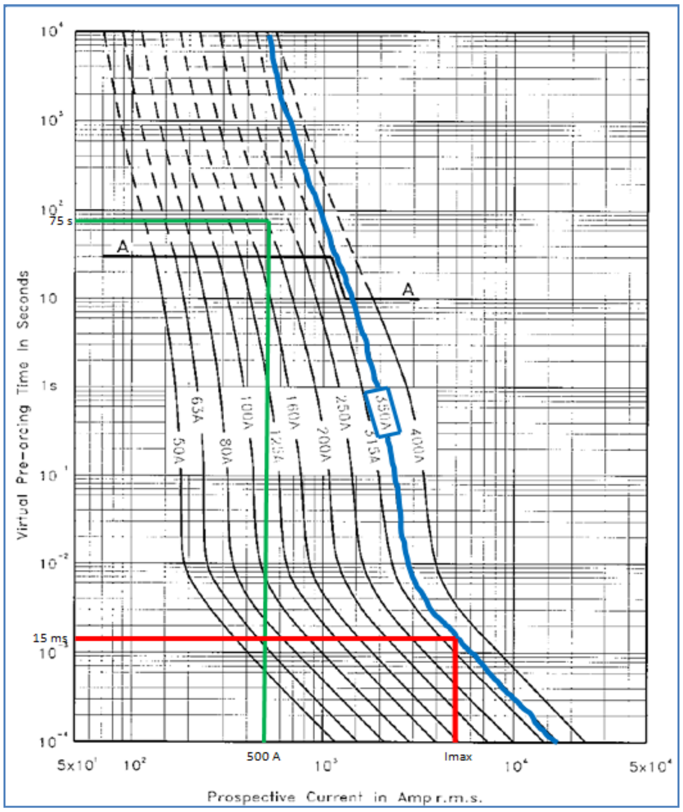

Figure 46: Fuse Usage Specification Chart

Another proposed problem that affects fuse performance is the claim of fuse fatigue. The idea is that fuses perform differently after many operational cycles. At the current time the team lacks the hardware to test the fuses for fast acting high current failure, but possible testing locations to complete this study are currently being investigated. However the other two parameters, resistance to failure under normal operation and fatigue studies could be investigated. The proposal is to use the smallest fuse possible that does not fail under the duty cycle of BB3 racing. The testing involved connecting the fuse a large battery pack cycler and performing similar racing profiles. The experimental set-up is shown in Figure 47.

Figure 47: Fuse Testing Experimental Set-Up

Two fuses were tested. The first was simply operated at the continuous racing current until failure. This fuse accepted fully vehicle current for more than 33 minutes before failing, far exceeding the two minute needed run time. The second fuse was run through 30 race cycles, allowed to cool, and then run until failure. This fuse failed after 25 minutes, leading to the conclusion that there are some effects of fatigue present in high current cycles. Pending high power fast blow testing, the Cooper Bussmann 170M3697 fuse was deemed to be appropriate for use in the BB3. Thermal images from the testing can be seen in Figure 48.

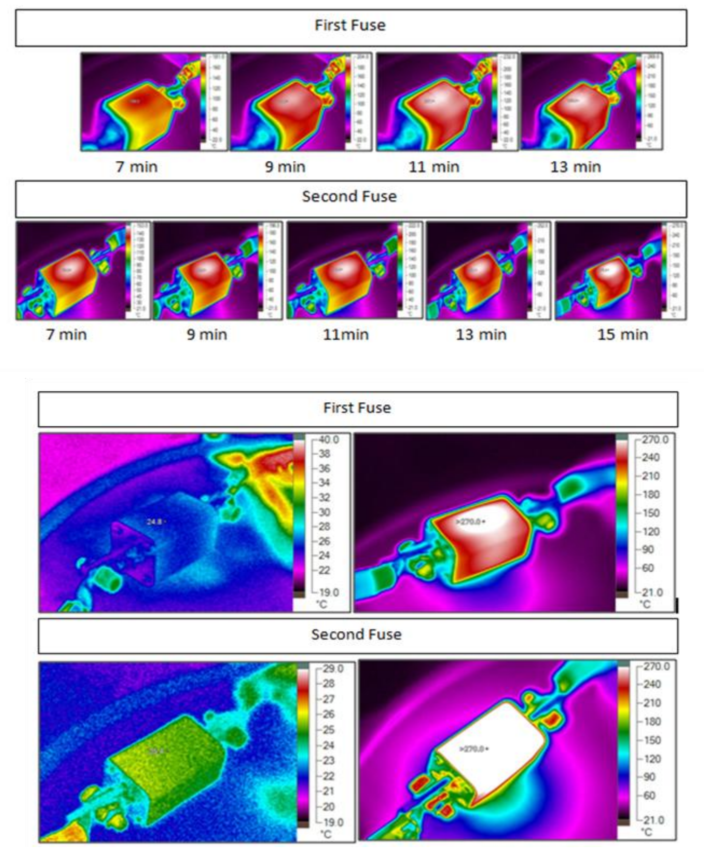

Figure 48: Fuse Testing Thermal Images

4.3.2 Wire Selection

In a similar manor to the fuse testing, various wire sizes were studied to pick the optimum combination of performance and weight for use in the BB3. Measures of temperature increase and resistive losses were considered for this study. Thermal images from the testing can be seen in Figure 49 and the test results can be seen in Table 4.

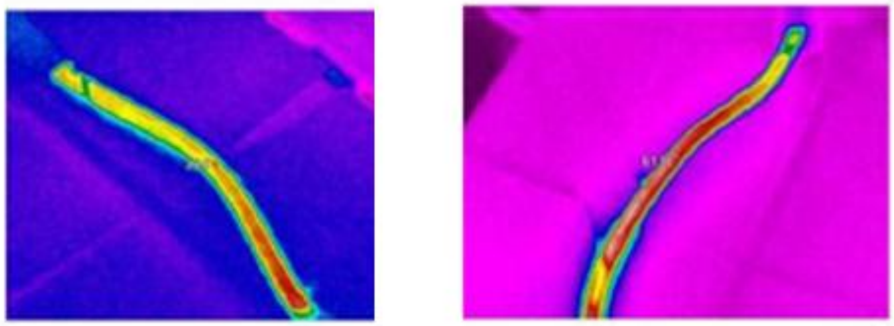

Figure 49: Wire Testing Thermal Images

Table 4: Wire Testing Results

Wire Size	Conductor Area	Current Density	Losses	Temperature
[AWG]	[mm^2]	[Amps/mm^2]	[mV/ft]	[C]
2	33.6	33.6	76-89	27-58
2/0	67.4	7.2	42-46	25-38
4/0	107	4.5	28-30	31-36

As expected the largest wire, 4/0, had the best overall performance, but is the largest, heaviest, and most difficult to route in the vehicle. The smallest wire, 2 Gage, showed significant heating and losses and was deemed unworthy. The middle wire size, 2/0 showed reasonable performance while greatly improving on the size, weight, and routing abilities of the larger wire. 2/0 wire was selected as the primary power wire for all pack level electrical wiring.

4.3.3 Contactor Selection

Contactors, unlike the other electrical devices investigated, do relay fairly heavily on their operating specifications. The two specifications of great important are the voltage rating and the rating for current the contactor can break. If the voltage supplied is too great the contactor can arc and become completely ineffective. The current rating is of particular interest. While a contactor might be able to sustain high levels of current flow its ability to break that current flow under power is quite a different story. It is simply not practical to have contactors that can break the fully current flow at every stage of the system due to their large size and extreme cost. As such high current contactors are placed within the inverter, but the other contractors are considered only as zero current switching devices. While there is some potential that the smaller contactors could break high than rated currents and this would be attempted in an emergency where other devices had failed, this is unlikely and is not relied upon. A contactor that the team has had historically great performance from this the Kilovac Czonka series shown in Figure 50. This is the contactor that was selected for all non-break current applications on the vehicle.

Figure 50: Kilovac EV 200 Czonka III

4.3.4 Connector Selection

In the recent past, reasonably sized high power connectors were not commercially available, and thus in previous generation Buckeye Bullet battery packs undersized connectors were used. While this never lead to a direct problem, the unreliable design and non-sealed nature of the connectors did. Thankfully a new line of connectors from TE Connectivity is on the market and being made available to the team. The HPB 800 line meets the BB3 needs exactly and makes for a reliable sealed high power connection. These connectors will be used to at all pack level connections and for the manual service disconnect.

Figure 51: TE Connectivity HPV 800 High Current Power Connector

The final overall BB3 control and power systems schematics including pack protection devices is shown below in Figure 52.

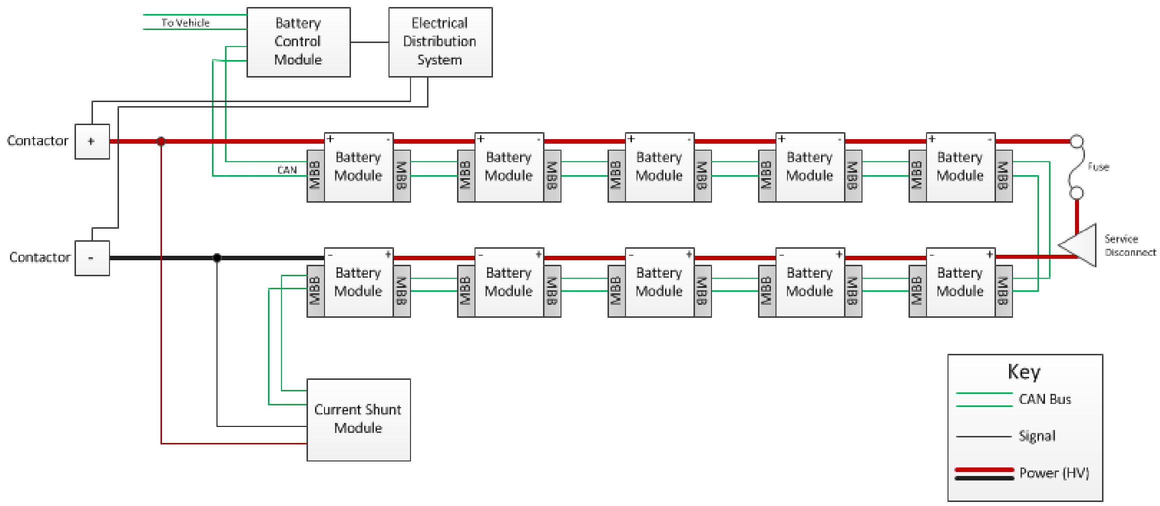

Figure 52: BB3 Battery Pack Schematic

4.4 Charging Considerations

An extremely important auxiliary system is the battery charging system. As previously mentioned the decision was made to execute a charger between run strategy verses a battery swapping strategy. This was especially a goal of the manufacturer to demonstrate the capabilities of the cells. The means that during an FIA record attempt between 20 and 40 minutes are available to completely charge the system. Because being at full power for a international record run is so critical all for the charge sizing exercise assumed the batteries would be fully depleted (to the minimum acceptable SOC) and would need to be recharged in 20 minutes. Charging strategies were tested at the cell level to verify sizing calculation. The proposed current SOC profiles are shown in Figure 53 Figure 54 respectively.

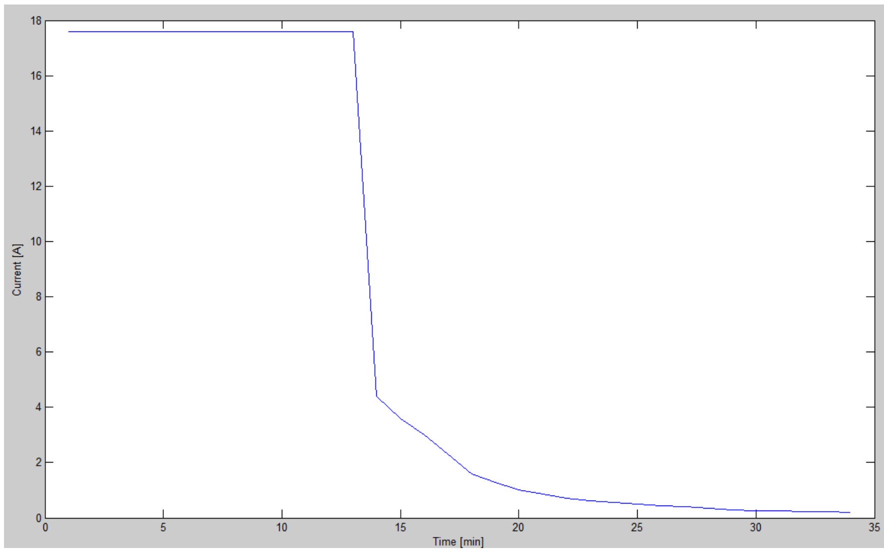

Figure 53: Battery Charging Current Profile

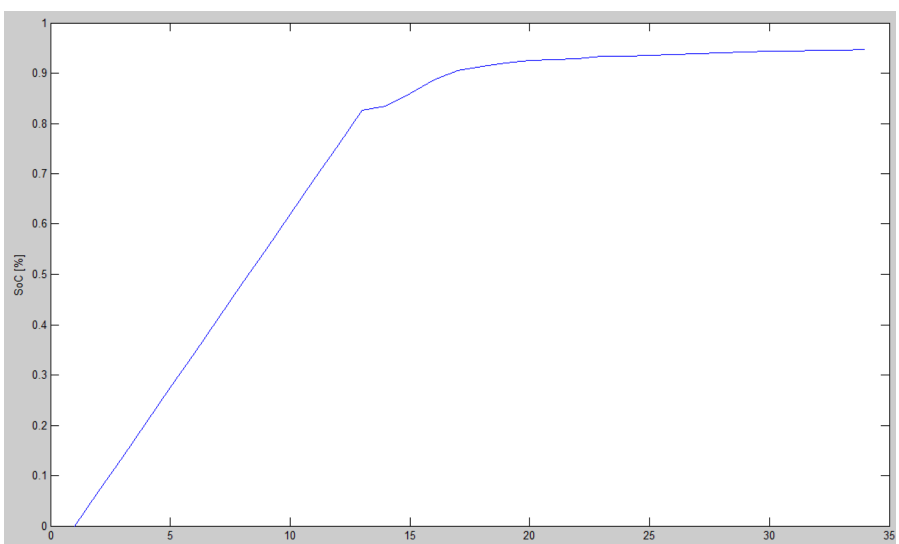

Figure 54: Battery Charging Rate

Assuming that 60 amp hours will be consumed during the run, approximately 180 kW of charging power is needed. After a long search for companies capable of supplying the needed equipment on a few solutions were found. In the end it was decided that three 75kW programmable DC power supplies would best fit the specifications. Because of the need for operation in harsh conditions of the salt flats including high levels of salt, water, wind, and heat, completely sealed water cooled models were selected. This use of 3 charges to simultaneously charge 8 battery packs will require some interesting connections and power balancing schemes that are still being developed. Also in development is the computer controlled optimized charging cycle. The selected hardware is shown in Figure 55 below.

Figure 55: Battery Charger Hardware

Once it was realized that due to national record rules the team need to be able to fully service the vehicle, including battery charging, away from the pits; an entirely new design project was presented in the form of a charging and service trailer. Since there is no "grid" water source on the salt flats a closed loop water chiller system to cool the chargers was needed. This system could also potentially cool vehicle motors and inverters during the turnaround period. The large and heavy refrigerant system specified to cool the battery cooling air was also included in the scope of the support trailer. Finally the trailer needed to contain some form of vehicle lift system so the tires, suspension, and body could be removed for complete vehicle inspection and service. This system is still in the design phase. With each of the chargers taking up a significant footprint and weighing in at nearly 1000 lbs as well as the water cooling system and tool boxes also hitting the 1000 pound mark as well it became clear that this is no small support trailer. Additionally a ~300 kVA gen-set to power the trailer with 480 V 3 phase power will also have to be hauled by a separate truck to the service site. A summary of the necessary equipment is shown in Figure 56.

Figure 56: Vehicle Service and Charging Trailer Components

4.5 Other Safety Considerations

4.5.1 External Indicators

One concept that has come from a great many years of racing experience with the team is the implementation of an external vehicle status indicator system. Because electric powertrain make nearly no noise at idle, engineers, bystanders, and track officials rarely know the state of the systems. This has cause a great number of problems in the past and is frequently unsettling for the team and those approaching the vehicle. The proposed solution to be implemented in the BB3 is an external LED pod with indicator lights. This pod could function much like the marking lights on an airplane. The proposal is to place an aerodynamic pod on the top surface of the tail fin. The various lights would indicate first if the overall vehicle controller is powered and active (red), next of the battery systems are active and contactors closed (yellow) and finally when the inverter is activated and contactors closed (green). The color scheme like a stop light indicates the vehicle's readiness to accelerate from a stop. A final set of lights would be very bright strobe lights which would be used to indicated an emergency. The possible triggers for these lights are currently under heavy investigation. Fatal error signals from any of the vehicle or battery controllers could trip emergency lights. The team is also investigating ground fault detection methods which could indicate a connection between the high voltage system and the vehicle chassis. Also included in this pod can be from and rear facing cameras. In addition to providing entertaining videos of the run, these cameras actually become a very important part of the data acquisition system as they are one of the few ways to monitor parachute performance and capture events as the unfold during the course of the run. A concept of the pod system layout is shown in Figure 57 below.

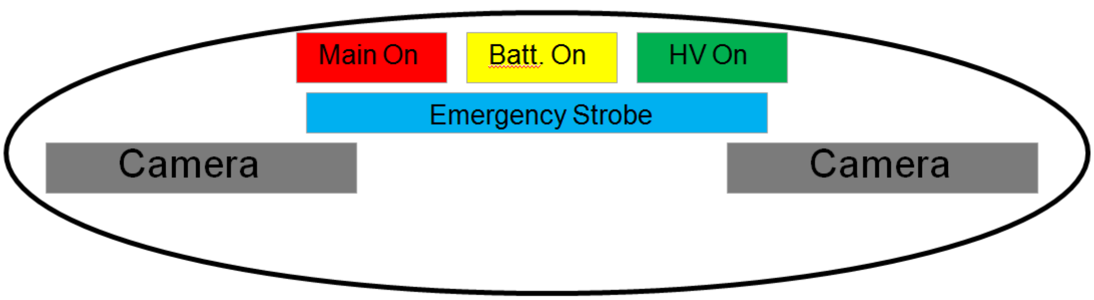

Figure 57: External Safety Indicator Layout Proposal

4.5.2 First Responder Preparedness

In the case of emergency first responders need to be informed quickly and effectively of the contents and protocols of dealing with a high power electric vehicle. In the context of racing this means preparing the onsite emergency teams at the track PRIOR to the racing event of the operation and specifications of the vehicle. Ideally this includes giving the teams an overview of the vehicle and allowing them to ask questions. The system proposed in the section above is a solution to give first responders a preparing of conditions that might be occurring. While they will probably not trust that no lights means the car is safe, a bright flashing light will indicate that there is a known problem and they should proceed with extreme caution. In the context of the workshop first responders to incidents need to be informed of the contents of the building and the location of specialized equipment needed for dealing with battery incidents. This equipment should be readily available and well marked.

4.5.3 Shop Safety

While it is not the focus of this document it should be noted that working with high voltage high power battery systems brings a number of needed safety protocols in the workshop. The team is currently in to process of performing a facility safety assessment. High power batteries in large quantities are not something a typical race shop is use to working around, and this brings concerns especially in an academic, mixed discipline shop. Many by-standers and students working on other programs have no idea what these devices are capability and do not know how to respect them. Proper labeling, storage, handling protocols, and emergency response methods are critical to running a safe program. Another important consideration is having the proper safety equipment available to operators and first responders. This includes high voltage gloves, face shields, fiberglass safety poles, properly rated fire extinguishers, and voltage rated insulated tools as seen in Figure 58.

Figure 58: 1000 Volt Rated Electrical Tools

4.5.4 Transportation Safety

A final area of safety consideration is that while transportation the batteries. The considerations and rules change when transporting cells verses pack verses batteries mounted in a complete vehicle. Lithium is a reportable hazardous material and transportation nearly always requires a hazmat licensed driver, special paperwork, and a plagued equipped vehicle.   There are two exceptions to these requirements. The first way avoid these complications is to transport less than 1001 pounds of batteries at a time. This weight requirement includes the batteries and the packaging they are in. While lithium batteries transported in small quantities still need to be in the proper packaging and well marked the transportation rules are much more friendly. The other way to avoid these complications and the preferred method of the Bullet team is to mound the vehicle in the race car. Batteries permanently mounted in a vehicle are considered part of the vehicle system and are allowed to bypass hazardous transportation rules. It is important for the team to consider these rules the consequences each time the batteries need to be moved. A violation of such rules can lead to thousands of dollars in fines and even time in jail. It is preferred that the modules come directly from the factory and only every leave the race shop as complete packs mounted in the vehicle. In the past the team has even found a way to mount space modules in the vehicle during transportation to the racetrack. Regardless of the laws of transportation each time the batteries are out of the direct control of the system engineers, precautions need to be taking to ensure the batteries are properly packaged and in a disabled mode. For the BB3 this means removing the manual safety disconnect and disabling the controller. It is also very importation to inform any drivers transporting the system of what they are carrying and what precautions should be taken in case of an accident.

Chapter 5: Pack Design

5.1 Packing Design Background

Work in the area of mechanical packaging and system integration into the vehicle began before the a battery cell was officially selected, and long before sample batteries were available for testing. A great deal of conceptual models were investigated. As previously discussed volumetric efficiency and minimizing the weight of the packaging components are key aspects of the battery packaging design and have a direct effect on overall vehicle performance. When developing a packing system the following concepts were considered:

- Safety
- Efficiency (Mass and Volume)
- Cooling Scheme Implemented
- Serviceability
- Readiness for Harsh Condition Operations (Salt, Wind, and Water at the Flats)
- Manufacturability
- Handling and Transportation
- Rigidity

First consideration is the module mounting strategy. Like any cube the modules have six sides. The modules have two possible mounting methods retaining bolts oriented vertically, or horizontally to the module. These two factors lead to 12 possible mounting schemes. Some of those 12 are duplicates of each other, and some would never be used, i.e. sitting the module on its top covers. In the end the 12 options were reduced to the two basic mounting schemes shown in Figure 59.

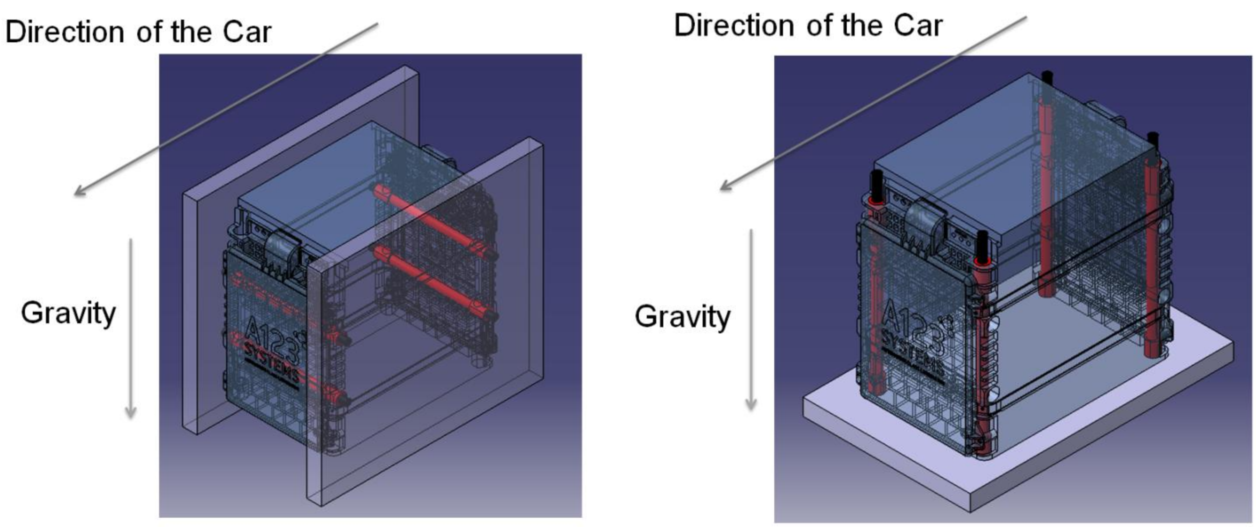

Figure 59: Possible Module Mounting Schemes

With these concepts in mind a great number of possible solutions were investigated. In fact more than 30 complete design concepts were designed and compared. Concepts utilizing machined elements, laser cut and bent sheet metal, stamped sheet metal, simple rail amounting, and composite shelves and tubes were investigated. Samples of this work can be seen in Figure 60 thought Figure 64.

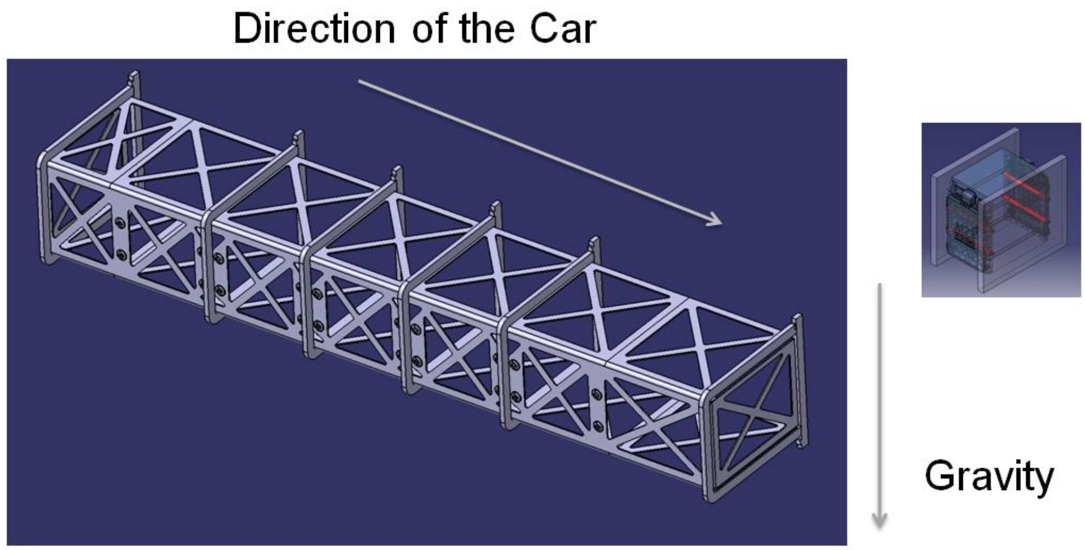

Figure 60: Laser-Cut and Bent Sheet Metal Packaging Design Concept

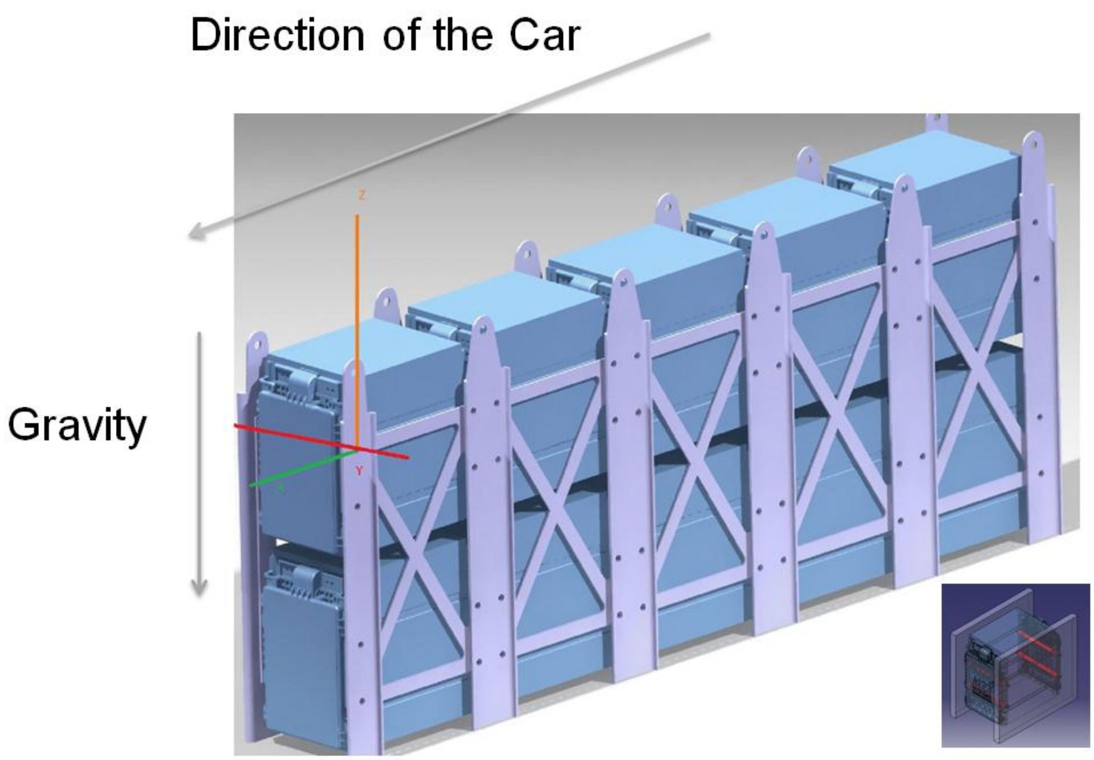

Figure 61: Multi Element Laser-Cut and Riveted Sheet Metal Packaging Design Concept

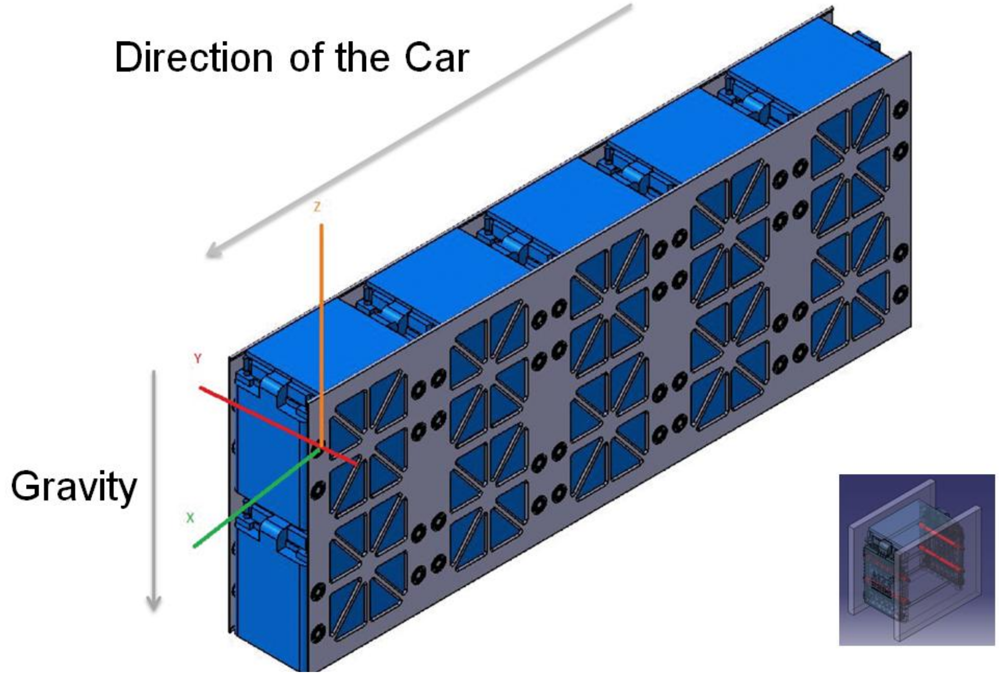

Figure 62: Stamped Sheet Metal Packaging Design Concept

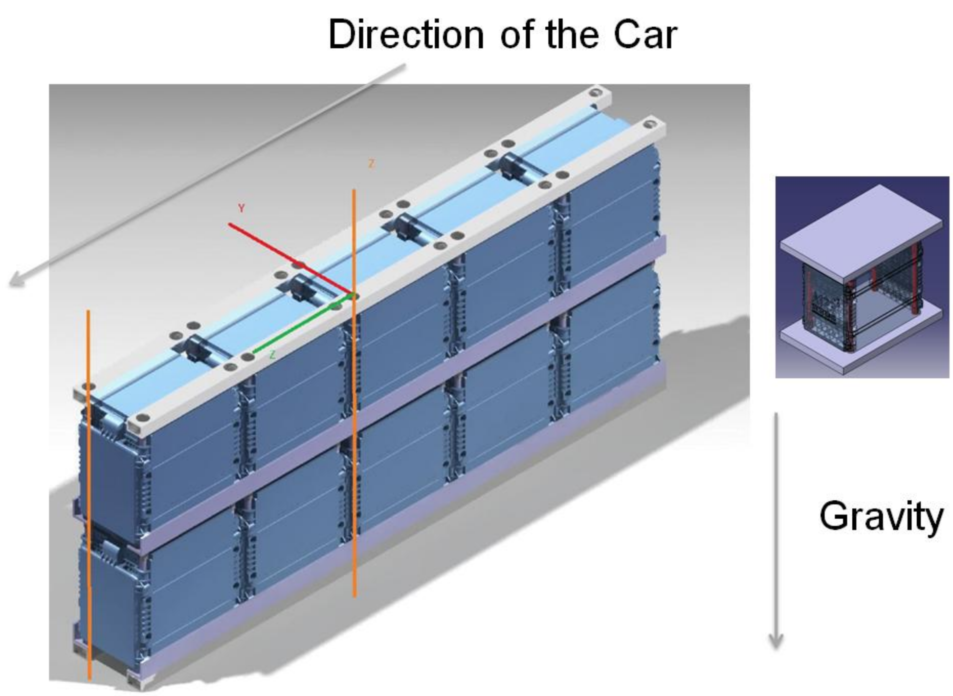

Figure 63: Simple Rail Mount Packaging Design Concept

As discussed in Chapter 3, scaled testing with similar cells and project power and thermal performance data led the team to utilize an aggressive cooling strategy with onboard liquid cooling plates. The plan was to have the system on board, but not actively cycle coolant during a run, but instead to flow off-board water during the record run turn-around (charging) period. In early 2011, this decision lead the team down a specific design path and a complete system was designed and proposed. As part of a senior capstone design project the pack shown in Figure 64 below was developed .

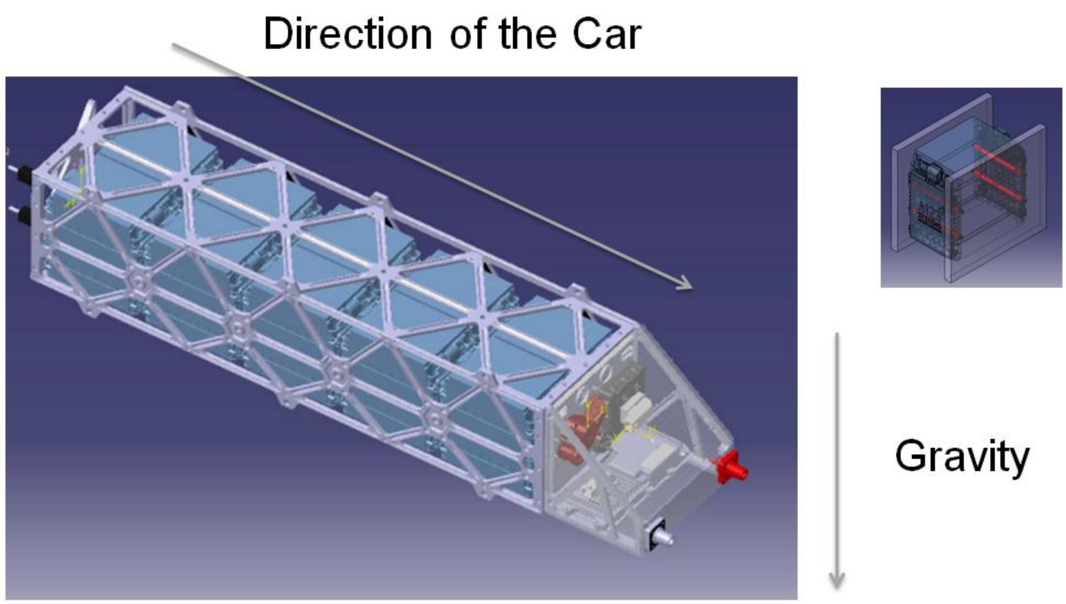

Figure 64: 2011 Battery Pack Proposal

While a great deal of good things came a result of this design, it had three fatal flaws which led to the need for a new packaging system.   The first and main flaw was the mounting scheme chosen. While the side clamp, compression scheme worked very well to compress the modules around a centrally located could plate, the team learned that it was not the preferred, or even approved mounting scheme in the eyes of the manufacturer. Mounting in this orientation effectively hangs the modules by the end plates and induces unneeded stress on the module structure. This problem was missed in the design reviews with A123 and not discovered until the prototype was presented to the packaging experts. The next major flaw was the basis of the design on a liquid cooling strategy, which was no longer required. The third flaw was the longer than expected manufacturing time. While all of the components were machined in house to make 10 more packs (to provide for the vehicle and spares) would have required and exceptional amount of time and capital. A more efficient method could have been implemented.

5.2 Proposed Packing Design

Once physical cells of the exact model to be used in the Buckeye Bullet 3 were available, testing showed that thermal performance was much better than expected. This led to the architecture and cooling strategies presented in Chapter 4. The newly proposed air cooling system warranted a complete redesign of the system layout and mechanical structure. While this was a bit frustrating due to the extreme amount of work invested in the liquid cooled pack, this presented an opportunity to start fresh and implement all the knowledge gained since the previous pack was designed.

The pack begins with ten modules stacked in two vertical rows of five modules as seen in Figure 65.

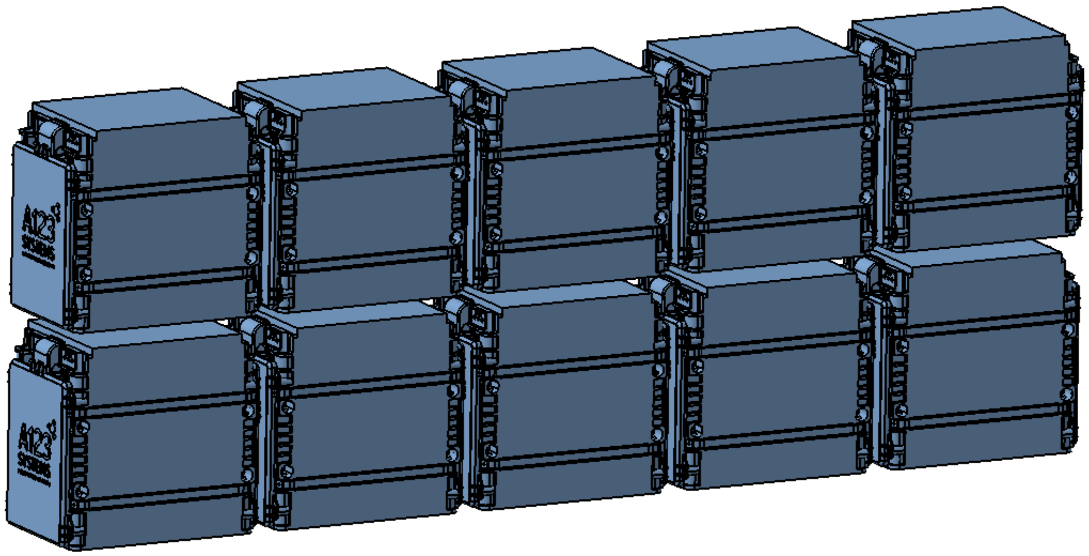

Figure 65: Packaging Design - Module Configuration

The basis for this packaging design is a carbon fiber structural tub. The choice of a carbon tub allows for an extremely ridged structure to be implemented with minimal weight. The carbon also allows for integral cooling channels and mounting points to be easily included in the design. Each tub holds 5 battery modules so two tubs are stacked on top of each other to form a pack. Aluminum inserters are be CNC machined and laid into each corner of the tub creating reinforced mounting points for electronics and accessories and rigid anchor points to mount the tubs to each other and the vehicle. Figure 66shows the tub design, Figure 67 displays the finite element model of the tub used for strength and failure modeling, and Figure 68 shows two tubs mounted together, the structural inserts, and top view of the tub. In the top view the cover is included which shows the slots provided to channel air down each side of the modules.

Figure 66: Packaging Design - Carbon Fiber Tub

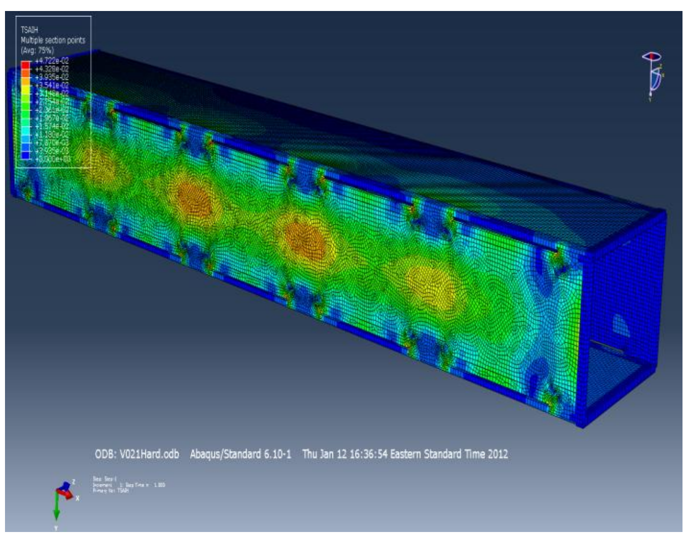

Figure 67: Packaging Design - Tub Finite Element Analysis

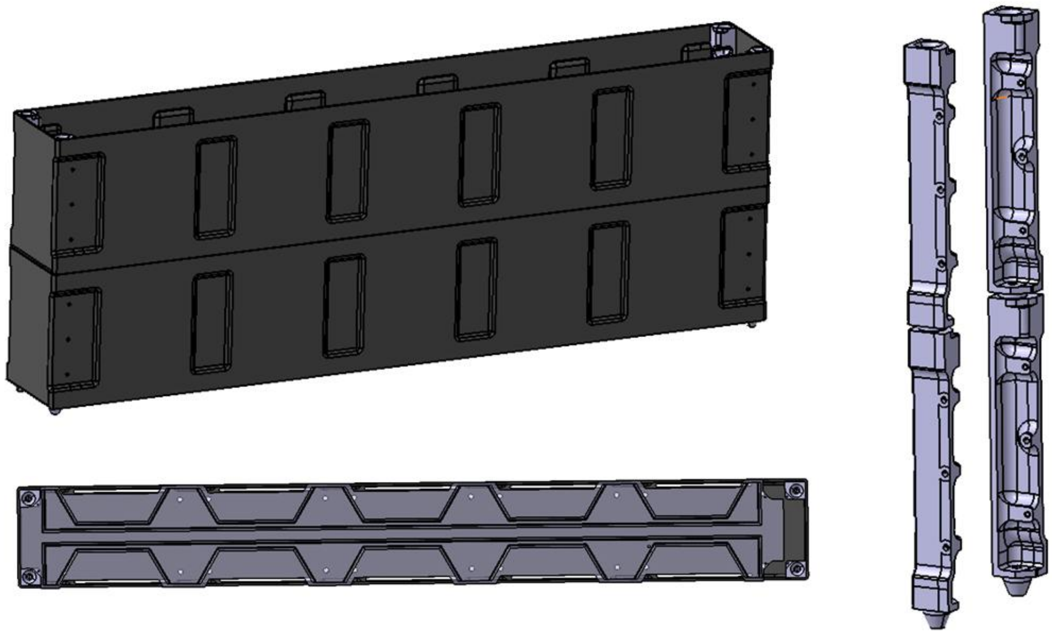

Figure 68: Packaging Design - Tub Configuration and Supports

The next consideration was the integration of the electrical control and circuit protection components. During the BB2.5 battery module build the team learned the importance of simple and easy access inter-module electrical connections. The previous pack's connections were very difficult to reach and tedious to install. This made the assembly process very time consuming and somewhat dangerous. Great care was taking to design a simple and easy system to integrate. Because the modules are very close to each other and the power connection are located on a vertical wall, before the module is installed in the pack an adapter block is bolted to the connection to create a 90 degree adapter for the connection face. Once all the modules are installed interconnections are made by bolting on a very simple connection bar from the top of the tube. There is no need to reach down in the pack with the operators hands or tools. The non-contact surfaces are covered in insulation material for added protection. This system can be seen in Figure 69.

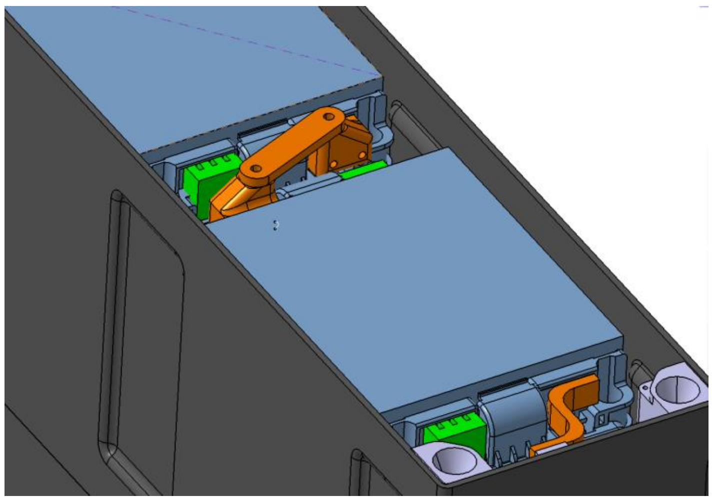

Figure 69: Packaging Design - Module Level Bus Bars

All of the battery management system hardware including the BCM, CSM, EDM, pre-charge circuit, and output power connections are packaged in a box at the end of the module. Insulative Garolite material will be used to construct the box. This can be seen in Figure 70 below.

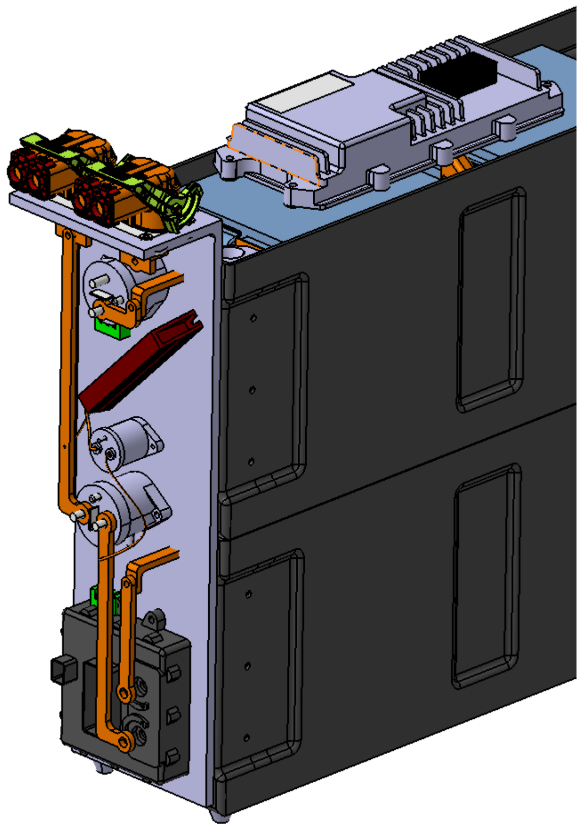

Figure 70: Packaging Design - Supervisory Electronics

On the opposite side of the pack the manual service disconnect and the fuses are packaged. The half pack location was chosen for these devices as it when either device is utilized it brakes the pack voltage in half, leaving two 450 V isolated systems as opposed to one 900 V system. The fuses are redundant and placed in series so that there is one fuse with each pack. The allows a fuse to stay with every half pack when the packs are in an assembly or service setting. If an accident occurs placing a pack in direct short, there will always be a fuse in each string of batteries. The manual service disconnect serves two purposes. First of all the connectors allow the two tubes that make up each pack to be electrically disconnected and separated very quickly and without tools. In addition this connecting cable can act as a manual system disconnect which allows the packs and thus the vehicles to be mechanically disabled ensuring that the vehicle cannot be operated and no electrical power can leave the batteries. This mode is ideal for service, transportation, and trade show type events. This system can be seen in Figure 71 and the entire electrical system integration can be seen in Figure 72.

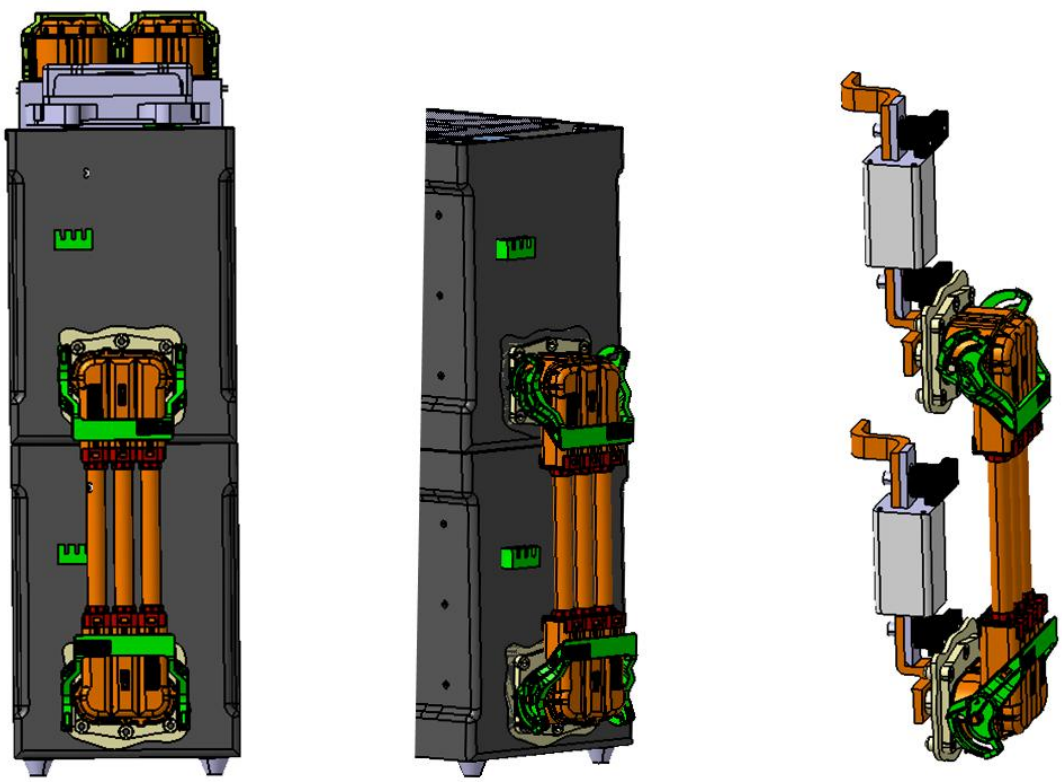

Figure 71: Packaging Design - Manual Service Disconnect and Fuses

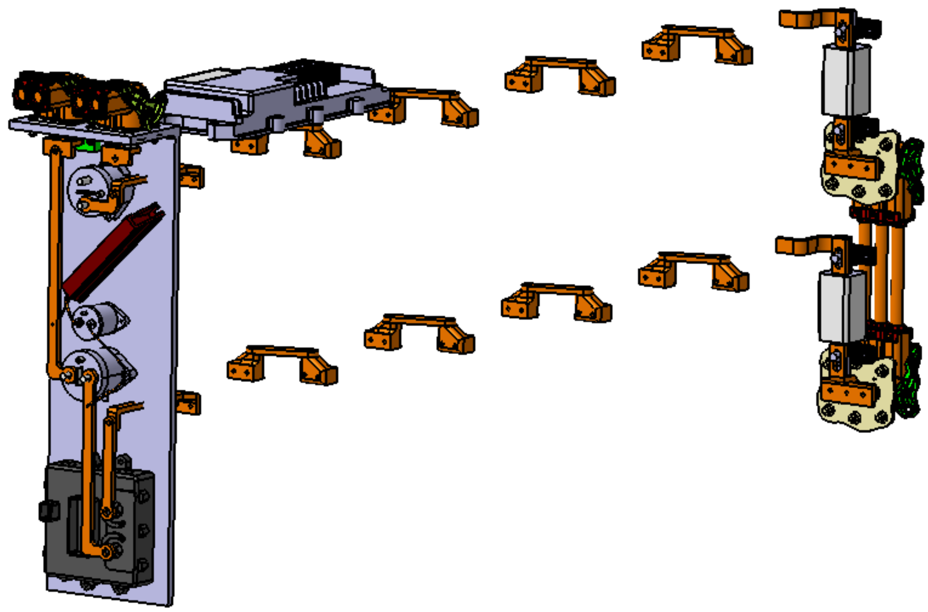

Figure 72: Packaging Design - Complete Electrical System

The entire pack design without the tubes can be seen in Figure 73 and the complete pack can be seen in Figure 74 and Figure 75.

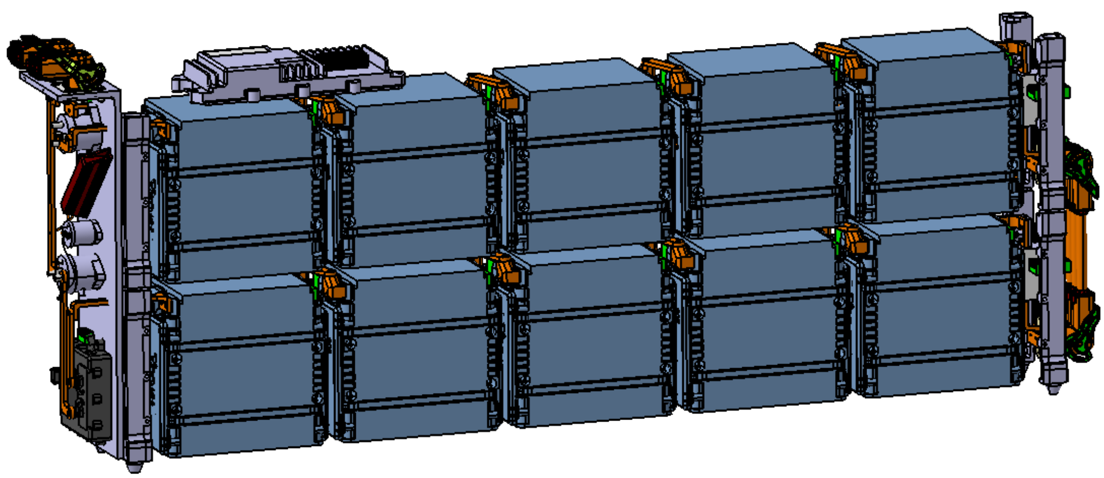

Figure 73: Packaging Design - Complete Pack Without Tubs

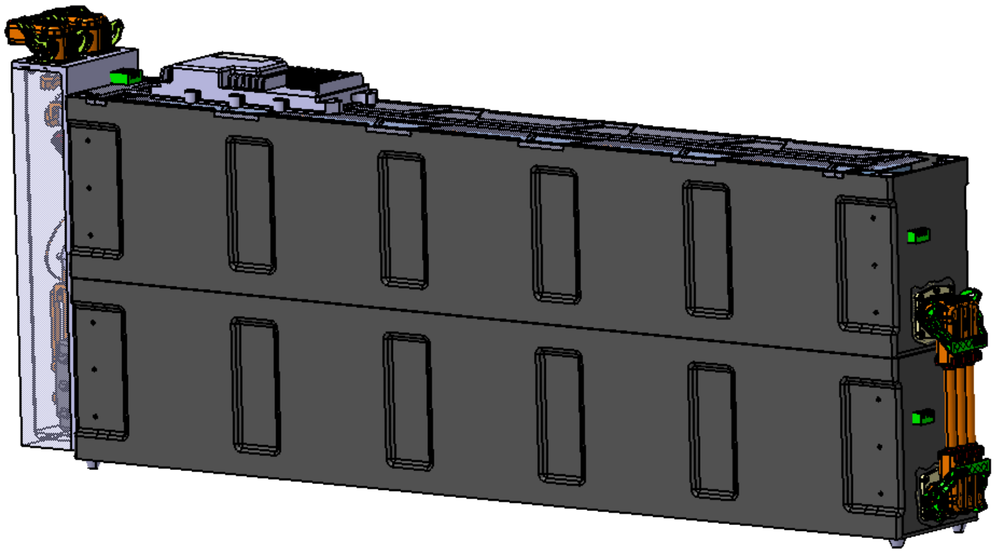

Figure 74: Packaging Design - Complete Battery Pack Left Side View

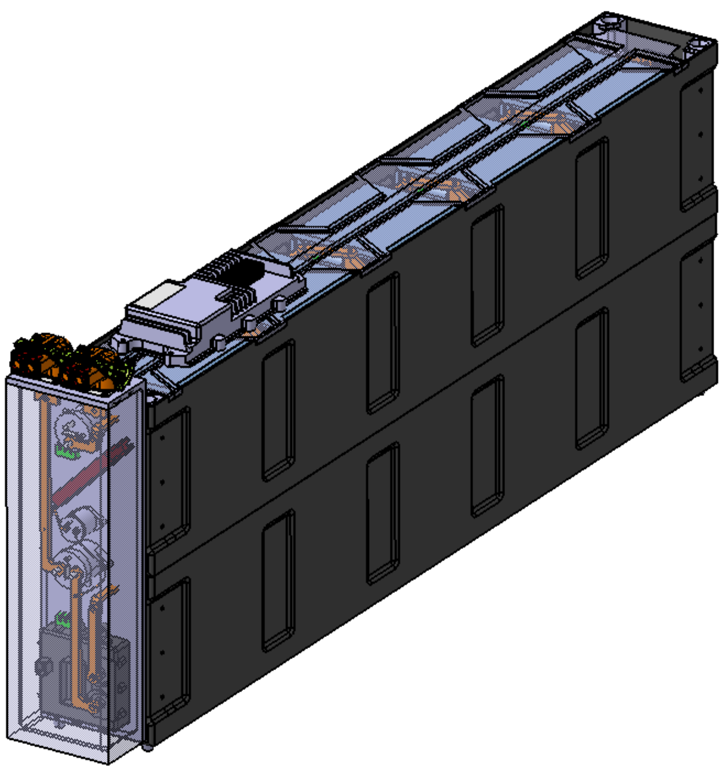

Figure 75: Packaging Design - Complete Battery Pack Right Side View

Chapter 6: Modeling and Simulation

Creating a model of a battery cell can be extremely useful for modeling complete battery system performance and rapid simulation and optimization of various the battery pack architectures. Integrating a detailed battery model into the overall vehicle simulator allows for more accurate performance simulations of the electric drivetrain, and overall vehicle performance.

In the simplest terms a battery can be considered a voltage source with a lumped internal resistance as shown in the circuit in Figure 76. This model is considered the zero order model.

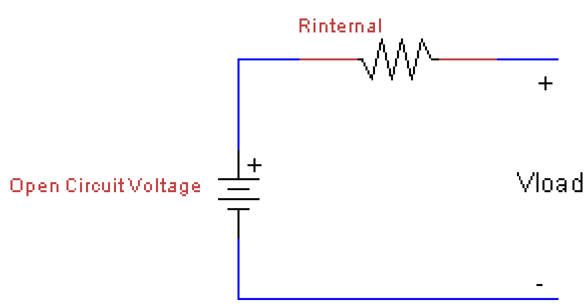

Figure 76: Zero Order Battery Model Circuit

A zero order model allows the basic operation of a cell to be mapped, but does not capture the transient performance of the cell very well at all. To better track transient performance a higher order model must be implemented. The first order model shown in Figure 77, known as the Randal model, is a very common and effective modeling technique. In this model an additional resistive and capacitive element are placed in parallel and the parallel block is combined in series with the first order model. If extremely accurate tracking of transient response is required, even higher order models can be used, but they are not necessary for the scope of this project.

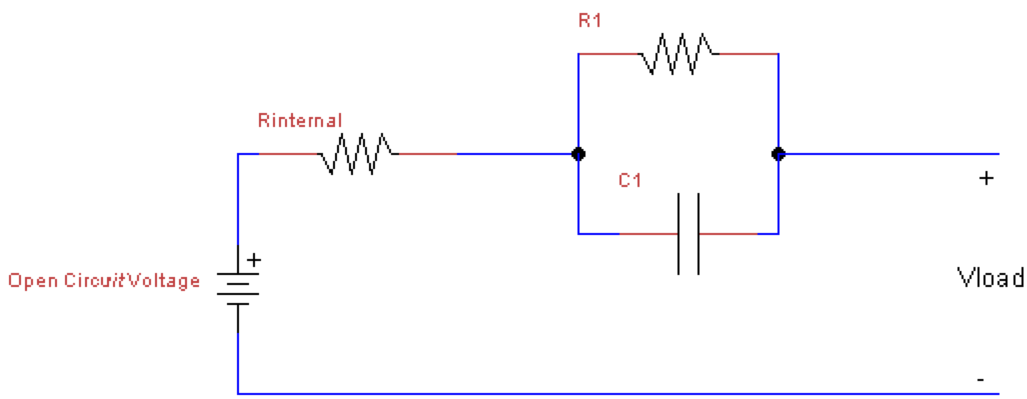

Figure 77: First Order Battery Model Circuit

Once a modeling scheme is chosen the next task is to obtain coefficients for the resistances and capacitances present in the model circuit. This task is accomplished using the standardized HPPC tests presented in Chapter 3. From these experimental procedures, calculations to obtain the coefficients are also defined in the Freedom Car Manuel which specifies the HPPC testing procedures.

The general schematic of the model layout is shown in Figure 78 below. State of charge and current temperature are continuously calculated. Base on current request as an input, and the estimated SOC and cell temperature, a voltage under load is calculated and output.

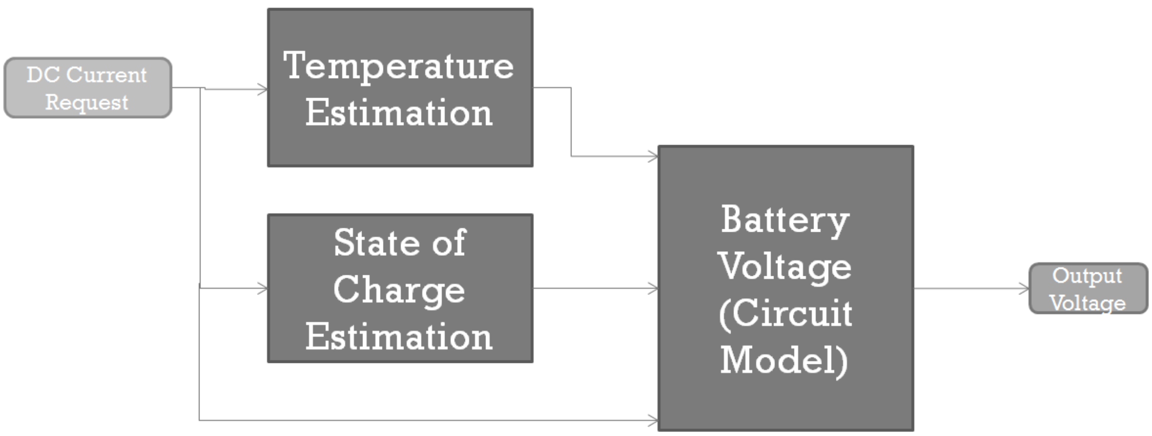

Figure 78: Battery Model Schematic

The next step towards creating a model is developing the necessary equations. These equations are presented in Equation 3 through Equation 7 below.

Equation 3: State of Charge Calculation for Battery Model

$$\%\,SoC = \left(Cell\ Capacity_{Nominal} * \int (Current)\ dt\right) / Cell\ Capacity_{Nominal}$$

Equation 4: Temperature Calculation for Battery Model

$$Temp_{current} = Temp_{initial} + \int \left(Current^2 * R_{internal} * \frac{1}{mc}\right) dt$$

Equation 5: Internal Resistance Calculation for Battery Model

$$R_{intenal} = R_{internal\ single\ cell} * \frac{\#\ Series\ Cells}{\#\ Parallel\ Cells}$$

Equation 6: Voltage Under Load Calculation for Zero Order Battery Model

$$V_{Load} = V_{OC} - R_{internal} * Current$$

Equation 7: Voltage Under Load Calculation for First Order Battery Model

$$V_{Load} = V_{OC} - R_{internal} * Current - R_1 * Current$$

$$where\ R_1 * Current = V_{capacitor} = \int \left[\frac{Current}{C_1} - \frac{V_{capacitor}}{C_1 * R_1}\right]$$

The equations above are then used to develop a block diagram in simulink modeling software. This simulator has been previously set up by the team and is ready for implementation once the parameters for the BB3 cells are determined. The top level and first sub level block diagrams are shown in Figure 79 and Figure 80.

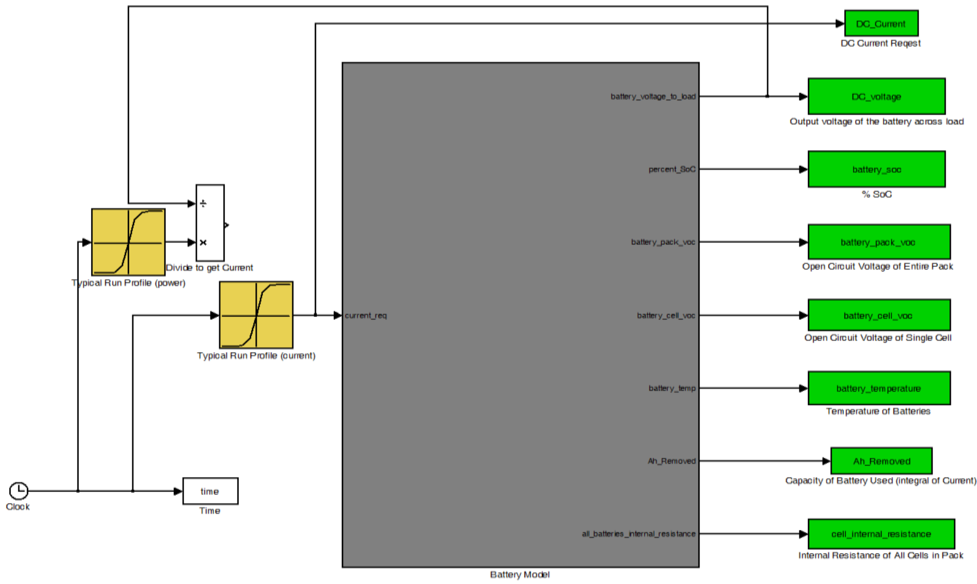

Figure 79: Top Level of Simulink Battery Model

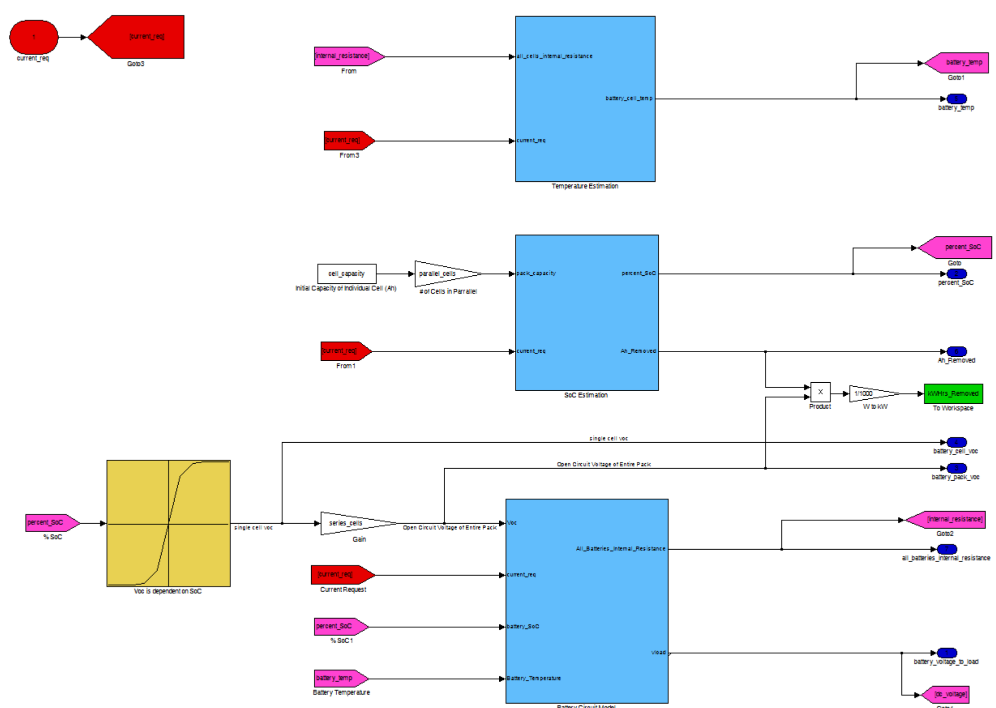

Figure 80: Second Level of Simulink Battery Model

Some baseline testing was done to prove the validity and implementation of the model. Parameters for a zero order model were developed and the data form simulation was plotted with the experimental test data. As seen in Figure 81 the basic operating points showed reasonable coloration, but the transient response to varying inputs did not correlate well as all. In the first a first order model as described above will be implemented to better match the experimental conditions.

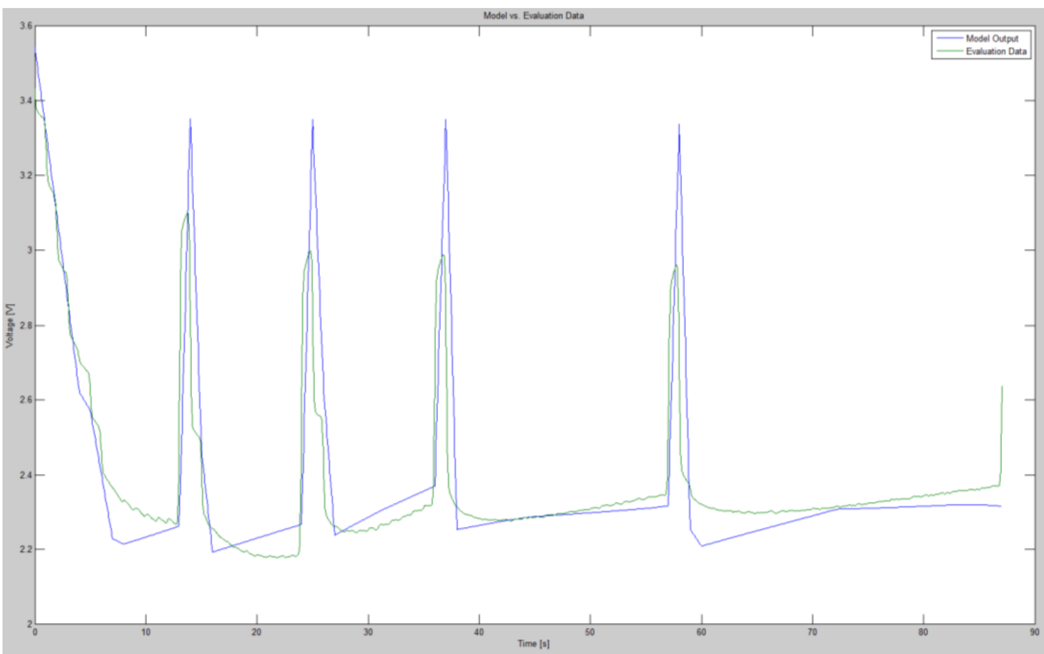

Figure 81: Simulated vs. Experimental Battery Voltage with Zero Order Model

Chapter 7: Future Work

The author will continue on to a masters degree in mechanical engineering and continue to developed the work presented in this thesis. The first step will be to build a complete prototype of the battery pack described in chapter 5. A physical prototype will allow the proposed manufacturing and assembly methods to be proven as well as providing an opportunity to test the entire integrated system. In parallel with the prototyping of the pack additional thermal testing of the proposed cooling strategy will be investigated. Fully insulated thermal tests showed that a minimal amount of heat needed to be removed from the packs between racing runs so the team moved forward with confidence in the decision that an air cooling system would be sufficient. While the packaging design includes air flow channels along the side of each module, very little testing has been completed to investigate the actual heat removal capabilities of forced conduction system, or to optimize the flow channels design. With a mock up of the system complete, a great deal of validation and optimization testing can be completed.

The next area of future work involves additional fuse testing. During fuse selection, the fuses were tested to make sure they would not blow under normal race operation conditions, and the concept of fuse fatigue was investigated, but the fuses were not tested for fast acting failure current. It is of interest to know how much current needs to be drawn to cause the fuses to fail at a time of 1 second, 10 seconds, and 60 seconds. This type of extreme current testing cannot currently be performed at the Center for Automotive Research, but testing strategies and outside suppliers are currently being investigated for future testing.

Now that the actual battery cell (correct chemistry and packaging) to be used in the Buckeye Bullet 3 is available for testing a full set of characterization tests as described in Chapter 3 will be preformed. The data from additional power and thermal tests will help to validate the design proposal presented in this document. More importantly the full characterization utilization HPPC tests across many temperature and states of charge will allow for the development and implementation of a full battery model, as described in Chapter 6, into the Buckeye Bullet 3 complete vehicle simulator. The framework for thermal and power models has been created, but a great deal of testing and validation is needed to produce a functional and accurate model. The scope of the graduate thesis will expand to include the interactions between the battery system and the electric traction powertrain. Optimization of the operating parameters will be investigated to promote overall vehicle performance. The final steps will be building the battery system and implementing it into the vehicle, and testing and tuning the system for optimal performance. Following recommendations presented in this document and continuing to develop the system as described in this chapter will allow for the greatest opportunity to safely and efficiently set an electric vehicle world speed record in excess of 400 miles per hour.

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